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Kaolinitic weathering zone on Precambrian basement rocks, Red River Valley, eastern North Dakota and northwestern Minnesota

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KAOLINITIC WEATHERING ZONE ON PRECAMBRIAN BASEMENT ROCKS, RED RIVER VALLEY, EASTERN NORTH DAKOTA AND NORTHWESTERN MINNESOTA

by
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This thesis submitted by Lynn Irvin Kelley in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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Department Geology

Degree Master of Science

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Date Nov. 26, 1980

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure

LIST OF TABLES

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ABSTRACT

A suite of 26 drill cores recovered from the Red River Valley Drilling Project has provided new information on the Precambrian basement of eastern North Dakota and northwestern Minnesota. Basement rocks in this area consist of intermediate to felsic coarse-grained massive or gneissic rocks, and intermediate to mafic metavolcanic and metasedimentary schists. The Precambrian rocks of the region are interpreted to be a buried extension of the Superior Province of the Canadian Shield, and are divided into terranes of granitic rock and mafic schist, on the basis of drill-hole samples, patterns seen in Superior Province rocks which crop out to the east, and regional geophysical trends.

In the southern part of the Red River Valley, a thick (up to 200+ ft. (75m)) weathering residuum is developed on the upper surface of the Precambrian, generally, but not exclusively, where the Precambrian is directly overlain by Cretaceous rocks. Where the deepest, least weathered rocks are foliated, ghost-like traces of the structures can be seen in slightly to moderately altered weathering products. Scanning electron microscope/microprobe studies show that micas and feldspars are altered to kaolin-group minerals. Regardless of original rock type, the end product of weathering is generally a white, greenish, or light reddish brown kaolinitic clay containing suspended angular quartz grains. Trends in major element chemistry are similar to those reported in studies of modern, exposed weathering profiles.

Evidence from this study points to intermittent or episodic kaolinite producing chemical weathering, beginning prior to Ordovician sedimentation, and lasting until deposition of Cretaceous sediments. The weathering took place under humid subtropical conditions.

The results of this study also show that under identical weathering conditions, different rock types alter to very similar weathering products.

INTRODUCTION

General Statement

In the summer of 1977, 32 wells were drilled along the valley of the Red River, which forms the border between North Dakota and Minnesota (Figure 1). The Red River Valley Drilling Project was funded by Bendix Field Engineering Corporation as a part of a nationwide uranium resources evaluation program (Moore 1978). Twenty-six of the wells penetrated Precambrian basement rocks. The cores recovered from this project are the most extensive suite of samples of basement rocks of this region yet available.

Results of the project, with respect to uranium possibilities, were inconclusive. However, the drilling program did provide new information on the Paleozoic and Mesozoic stratigraphy of the eastern margin of the Williston Basin, and a number of Precambrian cores.

Studies have been undertaken to use information from the Red River Valley Drilling Project to further understanding of the Precambrian geology of this area (Moore 1978; Ray and Karner 1979; Karner et al. 1980; Kelley and Karner 1980).

In the southern half of the Red River Valley, the precambrian basement rocks are overlain by a thick (up to 200+ ft. (70m)) layer of greenish-white kaolinitic clay containing suspended angular quartz grains. The clay-rich material is apparently a weathering horizon developed on the basement rocks. It is generally, but not exclusively

Fig. 1. Area covered by Red River Valley Drilling Project (Moore 1978), and general tectonic features redrawn from King (1969).

Study Area

Edge of Phanerozoic rocks

Structure contours on top of Precambrian. C.I.= 1000 m.

Boundary of Superior (east) and Churchill (west) Precambrian tectonic provinces.

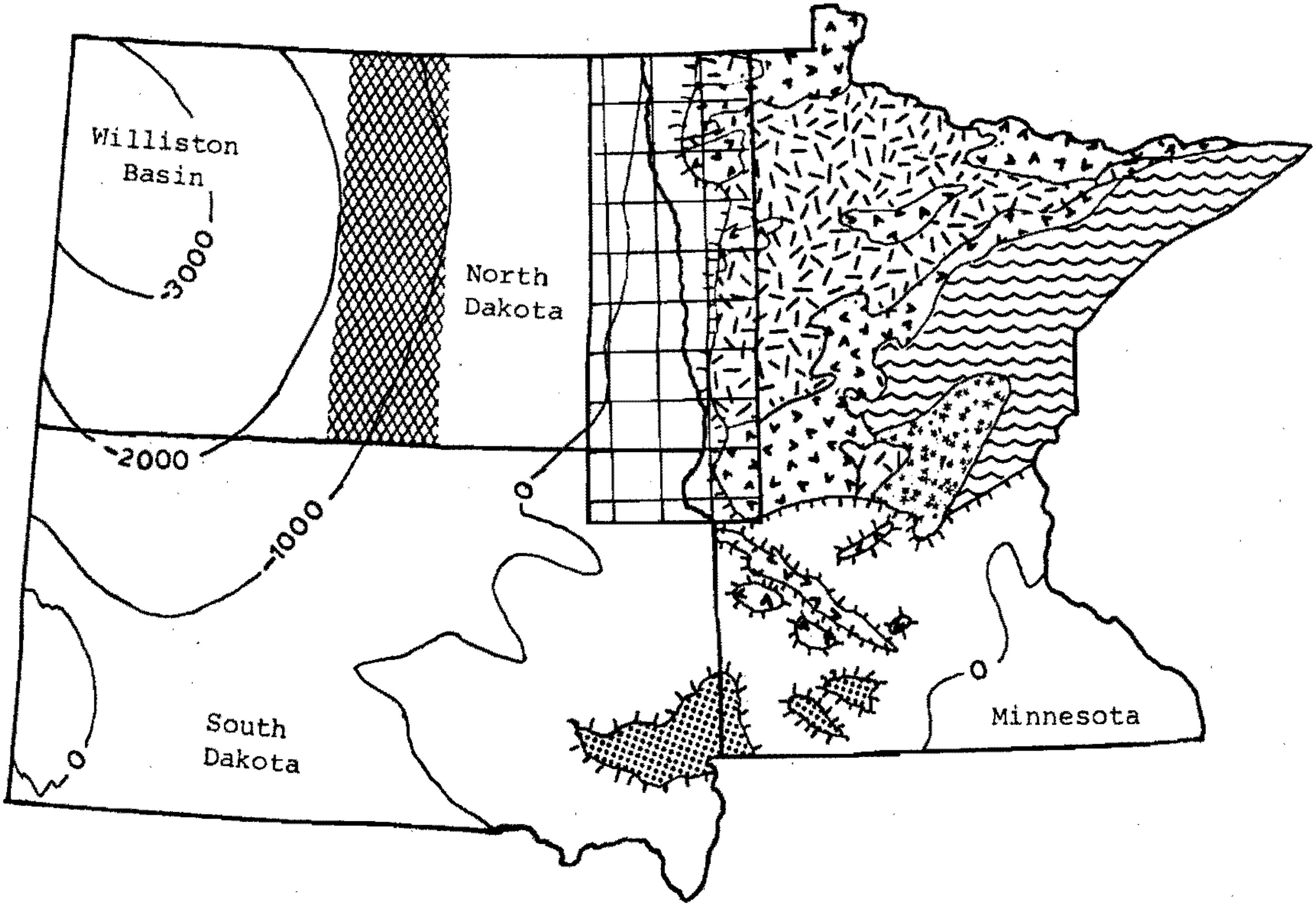
Proterozoic quartzite (Sioux)

Proterozoic granite and gneiss

Proterozoic metamorphosed volcanic, volcaniclastic, and sedimentary rocks.

Archaean granites and gneisses

Archaean metamorphosed volcanic, volcaniclastic and sedimentary rocks.


Williston
Basin
-3000
-2000
-1000
0
North
Dakota
South
Dakota
0
0
Minnesota

found where the Precambrian is directly overlain by Cretaceous sedimentary rocks, and is developed uniformly over a variety of parent rocks, including mafic schists and granitic rocks. The presence of this kaolinitic material extends westward the known boundary of a pre-Cretaceous weathering horizon studied in Minnesota by Goldich (1938), Sloan (1964), Parham and Hogberg (1964), Parham (1970; 1972), and Austin (1970; 1972).

The purposes of this study are:

1. To show that this material represents a weathering horizon, by documentation of chemical, mineralogic and physical changes from the basement rock to the kaolinitic material.

2. To compare the products of weathering of different basement rock types in the Red River Valley.

3. To contribute to the understanding of pre-Cretaceous climates, and the physical and chemical controls on this weathering horizon.

Regional Precambrian Geology

General

The Precambrian basement of the Red River Valley is a buried extension of the Superior Province of the Canadian Shield, which crops out in Ontario and northeastern Minnesota. Where exposed, Superior Province rocks consist of alternating northeast-southwest trending zones of metasedimentary and metavolcanic rocks of greenschist to amphibolite grade invaded by larger masses of rock which is granitic in composition and often gneissic. It has been suggested, from interpretation of regional geophysical trends, that the same pattern is present in the Precambrian subcrop under eastern North Dakota and northwestern Minnesota (Lidiak, unpublished manuscript; Ray and Karner 1979; Karner et al. (1980).

Muehlberger et al. (1967) used limited well samples and regional geophysical data, notably the Bouger gravity anomaly map of Woolard and Joesting (1964), to construct a basement geologic map of North and South Dakota as part of a study of basement rocks of the midwestern U.S. Their map shows bands of greenstone alternating with bands of plutonic rocks in the eastern Dakotas.

Moore and Karner (1969) conducted a geomagnetic investigation of an area of Pembina County, North Dakota where unusual difficulty in using magnetic compasses was noted by workers from the U.S. Geological Survey. They found two major magnetic anomalies, near the towns of Akra and Hensel. They attributed the anomalies to the presence of concentrated iron oxides in the underlying basement rocks.

The Akra and Hensel anomalies were drilled and cored by Amerada-Hess Petroleum Corp. in 1966. Richardson (1975) and Richardson and Karner (1975) reported on the petrography of the basement rocks of the cores. The rocks consist of various types of magnetite-rich rocks and mafic schists. The authors reported that gneissic rocks in northeastern North Dakota were dated at 2.14-2.57 bybp. They believed that the pattern observed in outcrop in Minnesota is continued in the basement under eastern North Dakota.

Okland (1978) completed a geomagnetic survey of Pembina, Walsh, and Grand Forks counties in the northeast corner of North Dakota. He found nine major magnetic anomalies, and several minor ones. He felt the anomalies were caused by "magnetic susceptibility contrasts" in the Precambrian basement rocks, and further stated that the trends in anomalies were likely caused by greenstone belts in the basement.

Moore's (1978) report of the Red River Valley Drilling Project included a summary of the types of Precambrian rocks penetrated in the wells, and a structure contour map on the Precambrian.

Ray and Karner (1979) used new information from the Red River Valley Drilling Project (Moore 1978) along with previously compiled information, to revise and update the North Dakota basement geologic map of Lidiak (unpublished manuscript). The basement rocks were divided on the basis of chemical and petrographic characteristics.

Karner et al. (1980) reported on chemical characteristics of coarse-grained rocks from the Red River Valley cores, and offered a further update of the basement geologic map.

Precambrian Geology of the Red River Valley

The Precambrian surface is penetrated at depths from approximately 300 ft. (100 m) in the southern Red River Valley to approximately 1200 ft. (370 m) in the northern part of the valley and dips to the west and north at a rate of about 20 ft./mile (5m/km) (Figure 2).

The general geology of the Precambrian basement of the Red River Valley is shown in Figure 3. On the map, greenschist to amphibolite grade schists alternate in northeast-southwest trending zones with coarse-grained massive or gneissic rocks of intermediate to felsic composition. Table 1 summarizes details of the Precambrian rocks penetrated in the Red River Valley Drilling Project. The rocks encountered resemble typical Archaean rock assemblages except for the near lack of mafic volcanic rocks. A meta-basalt in well 10 was the only

Fig. 2. Structure contour map of the Red River Valley Precambrian basement. Contour interval = 100 ft. Filled circles are wells which penetrated the Precambrian. Empty circles are wells which did not penetrate the Precambrian. Modified slightly from Moore (1978).

FIG 2
P. 8

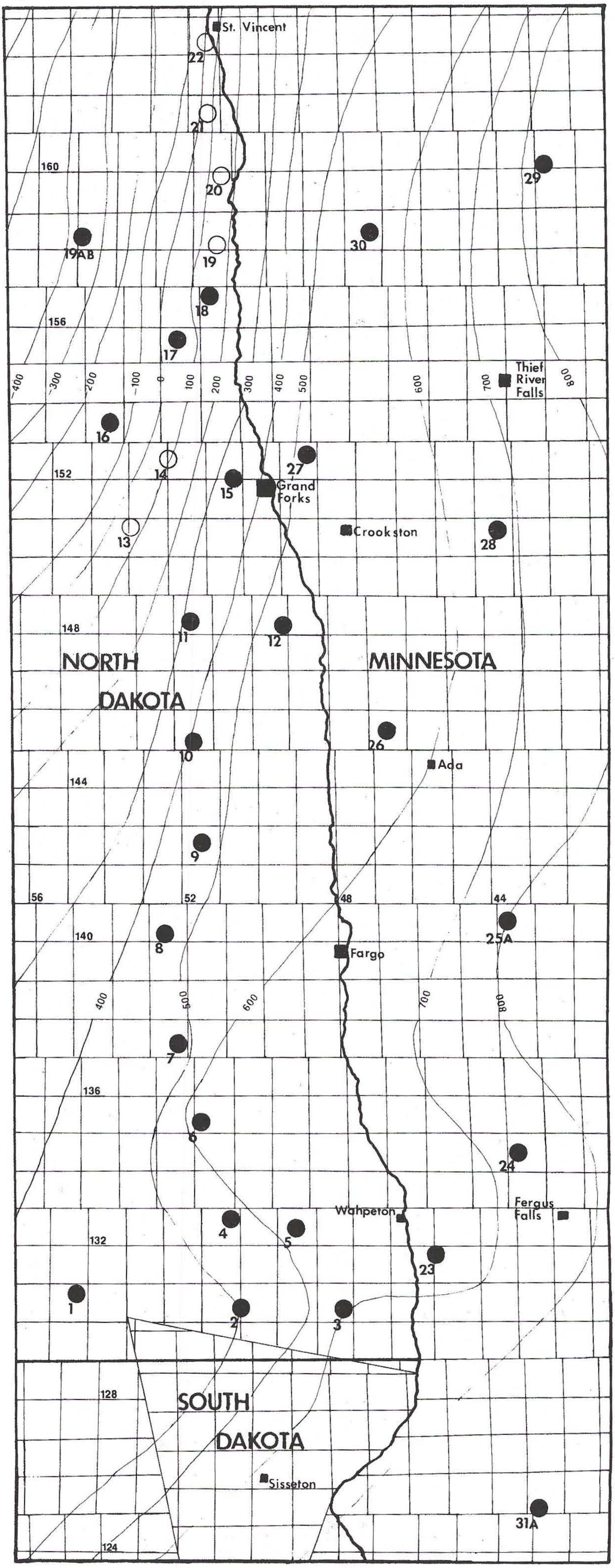
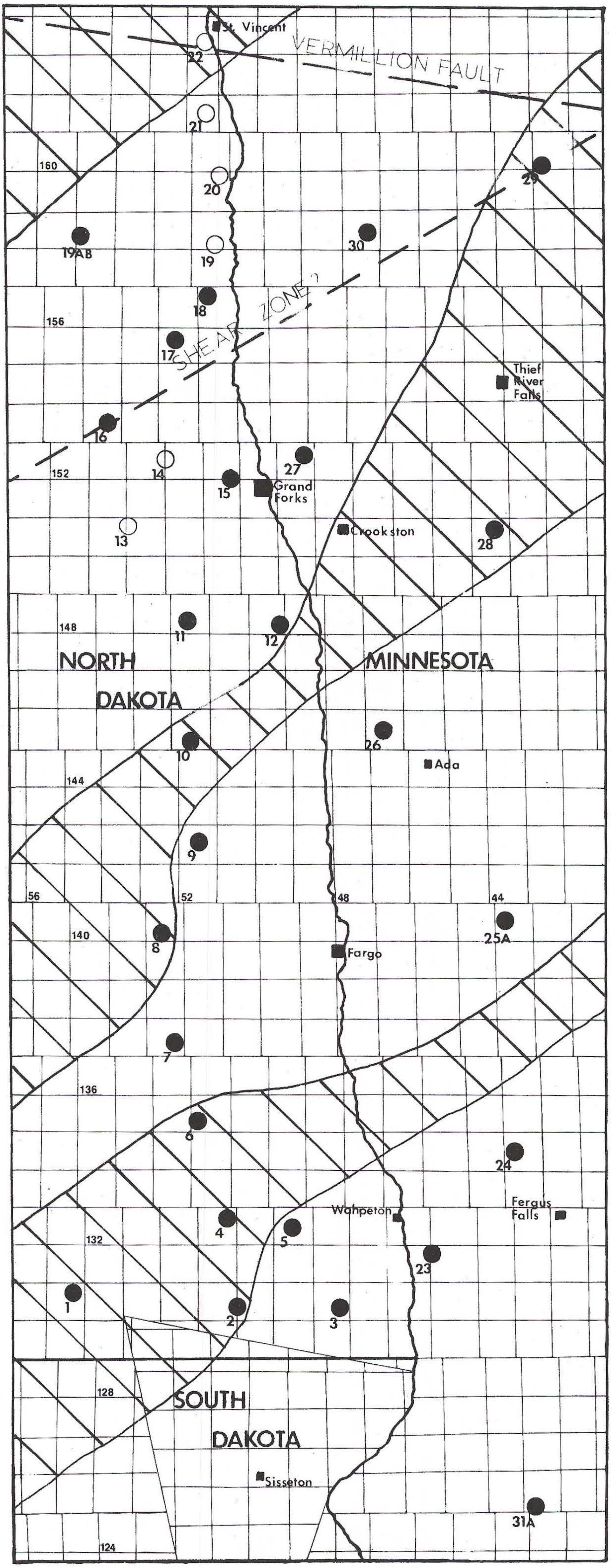

St. Vincent
22
21
160
20
29
19AB
30
19
18
156
17
Thief River Falls
-400
-300
-200
-100
0
100
200
300
400
500
600
700
800
16
27
14
152
15
Grand Forks
Crookston
13
28
148
11
12
NORTH
DAKOTA
MINNESOTA
10
26
Ada
144
9
56
52
48
44
140
8
25A
Fargo
400
500
600
700
800
7
136
6
24
Wahpeton
Fergus Falls
4
5
132
23
1
2
3
128
SOUTH
DAKOTA
Sisseton
31A
124

Fig. 3. Generalized basement geologic map of the Red River Valley. Contacts inferred from rock types penetrated and geophysical data. Base map from Moore (1978).

Granitic rocks and gneisses of granitic composition

Intermediate to mafic schists, greenstone

Fig 3
p10



St. Vincent
VERMILLION FAULT
SHEAR ZONE ?
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
19AB
30
29
28
27
26
25A
24
23
31A
160
156
152
148
144
140
136
132
128
124
56
52
48
44
Thief River Falls
Grand Forks
Crookston
NORTH DAKOTA
MINNESOTA
Ada
Fargo
Wahpeton
Fergus Falls
SOUTH DAKOTA
Sisseton

TABLE 1

PETROGRAPHIC DATA ON PRECAMBRIAN ROCKS PENETRATED IN THE RED RIVER VALLEY DRILLING PROJECT
Modified from Karner et al. (in preparation)

Well number	1-1	1-2	2
Landowner	Hanson	Hanson	Gaukler
Well location	11-130N-56W	11-130N-56W	19-130N-51W
County, State	Sargent, ND	Sargent, ND	Richland, ND
Depth to top of Precambrian	820 ft. (250 m)	820 ft. (250 m)	650 ft. (200 m)
Elevation of top of Precambrian	450 ft. (140 m)	450 ft. (140 m)	500 ft. (150 m)
Thickness of weathered zone	73 ft. (22 m)	73 ft. (22 m)	192 ft. (60 m)
Interval described	923 ft. (281 m)	924 ft. (281 m)	824 ft. (250 m)
Rock type	metabasalt	meta-tuffaceous* graywacke[1]	metagraywacke*
Grain size	fine	fine to very coarse	fine
Fabric	hyalopilitic-weakly foliated	conglomeratic-weakly foliated	schistose
Mineralogy (In percentages or order of abundance)	plagioclase pyroxene amphibole biotite chlorite calcite opaques apatite	quartz, 59 hornblende, 20 oligoclase, 8 biotite, 7 epidote, 2 chlorite, 2 opaques, 2 hematite, tr. sphene, tr. apatite, tr. Zircon, tr.	quartz, 35 albite, 24 biotite, 20 sericitized matrix, 12 chlorite, 5 muscovite, 3 hematite, 1 Zircon, tr. rutile, tr. garnet, tr.
Total mafics	----	31%	26%
Total SiO_2	----	----	----
Total Fe + MgO	----	----	----
K_2O/Na_2O	----	----	----

TABLE 1--Continued

Well Number	3-1	3-2	4
Landowner	Wieser	Wieser	Selzer
Well location	25-130N-49W	25-130N-49W	11-132N-52W
County, State	Richland, ND	Richland, ND	Richland, ND
Depth to top of Precambrian	294 ft. (90 m)	294 ft. (90 m)	511 ft. (155 m)
Elevation of top of Precambrian	696 ft. 212 m)	696 ft. (212 m)	547 ft. (167 m)
Thickness of weathered zone	145 ft. (44 m)	145 ft. (44 m)	219 ft. (67 m)
Interval described	454 ft. (140 m)	454 ft. (140 m)	731 ft. (225 m)
Rock type	tonalite	granodiorite[1] gneiss	talc-* chlorite Schist
Grain size	medium	medium	fine
Fabric	hypidiomorphic granular	gneissic	schistose-laminated
Mineralogy (In percentages or order of abundance)	calcic oligoclase, 48 quartz, 20 biotite, 12 hornblende, 4 epidote, 4 alkalic, 4 feldspar, 4 chlorite, tr. sphene, tr. Zircon, tr. apatite, tr.	plagioclase quartz microcline biotite hornblende chlorite opaques sphene apatite	quartz chlorite alkalic feldspar muscovite talc calcite pyrite
Total mafics	16%	----	----
Total SiO_2	----	60.5%	62.4%
Total Fe + MgO	----	11.4%	28.9%
K_2O/Na_2O	----	0.3	8.8

TABLE 1--Continued

Well Number	5	6	7
Landowner	Stallman	Solhjem	Saunders
Well location	22-132N-50W	29-135N-52W	23-137N-53W
County, State	Richland, ND	Richland, ND	Cass, ND
Depth to top of Precambrian	350 ft. (107 m)	430 ft. (130 m)	558 ft. (170 m)
Elevation of top of Precambrian	638 ft. (194 m)	635 ft. (194 m)	490 ft. (150 m)
Thickness of weathered zone	----	202 ft. (62 m)	140 ft. (43 m)
Interval described	382 ft. (116 m)	648 ft. (198 m)	734 ft. (224 m)
Rock type	quartz monzonite	meta-lapilli tuff*	foliated diorite
Grain size	fine to medium	very fine to coarse	medium
Fabric	allotriomorphic granular-mildly porphyritic	fragmental-pilotaxitic	hypidiomorphic granular
Mineralogy (In percentages or order of abundance)	oligoclase, 32 quartz, 26 perthite, 22 microcline, 9 biotite, 6 muscovite, 1 calcite, 1 epidote, tr. pyrite, tr. zircon, tr.	quartz chlorite muscovite calcite pyrite	plagioclase, 59 biotite, 17 hornblende, 14 quartz, 4 microcline, 4 calcite, 2 epidote, tr. zircon, tr. apatite, tr.
Total mafics	6%	----	31%
Total SiO_2	72.7%	----	56.9%
Total Fe + MgO	2.6%	----	12.7%
K_2O/Na_2O	1.4	----	0.5

TABLE 1--Continued

Well number	8A-1	8A-2	9
Landowner	Bartholomay	Bartholomay	Williams
Well location	33-140N-53W	33-140N-53W	15-142N-52W
County, State	Cass, ND	Cass, ND	Cass, ND
Depth to top of Precambrian	519 ft. (158 m)	519 ft. (158 m)	589 ft. (180 m)
Elevation of top of Precambrian	478 ft. (145 m)	478 ft. (145 m)	431 ft. (131 m)
Thickness of weathered zone	65 ft. (20 m)	65 ft. (20 m)	----
Interval described	608 ft. (185 m)	615 ft. (187 m)	598 ft. (182 m)
Rock type	chlorite schist*	migmatitic gneiss*2	trondhjemite
Grain size	fine to medium	medium	medium
Fabric	nematoblastic	banded-cataclastic	hypidiomorphic granular
Mineralogy (In percentages or order of abundance)	chlorite plagioclase quartz biotite opaques	calcic oligoclase quartz microcline biotite chlorite	oligoclase, 56 quartz, 26 microcline, 11 biotite, 4 chlorite, 3 muscovite, 1 epidote, 1 apatite, tr. zircon, tr.
Total mafics	----	----	7%
Total SiO_2	----	77.5%	70.6%
Total Fe + MgO		1.5%	2.5%
K_2O/Na_2O	----	0.4	0.4

TABLE 1--Continued

Well Number	10	11-1	11-2
Landowner	Dalrymple	Niemeier	Niemeier
Well location	27-145N-52W	21-148N-52W	21-148N-52W
County, State	Traill, ND	Traill, ND	Traill, ND
Depth to top of Precambrian	557 ft. (170 m)	680 ft. (210 m)	680 ft. (210 m)
Elevation of top of Precambrian	413 ft. (126 m)	303 ft. (92 m)	303 ft. (92 m)
Thickness of weathered zone	----	----	----
Interval described	557 ft. (170 m)	699 ft. (213 m)	702 ft. (214 m)
Rock type	metabasalt*	foliated granodiorite	trondhjemite
Grain size	aphanitic	medium	medium
Fabric	weakly layered	weakly foliated	gneissic
Mineralogy (In percentages or order of abundance)	hastingsite(?) plagioclase chlorite epidote magnetite calcite quartz alkalic feldspar	quartz alkalic feldspar plagioclase biotite opaques	quartz alkalic feldspar plagioclase biotite opaques
Total mafics	----	----	----
Total SiO_2	41.3%	----	65.4%
Total Fe + MgO	32.3%	----	5.0%
K_2O/Na_2O	0.1	----	0.2

TABLE 1--Continued

Well Number	12	15	16-1
Landowner	Odegard	Weekley	Lindholm
Well location	25-148N-50W	35-152N-51W	14-153N-54W
County, State	Traill, ND	Grand Forks, ND	Grand Forks, ND
Depth to top of Precambrian	302 ft. (92 m)	507 ft. (155 m)	1079 ft. (329 m)
Elevation of top of Precambrian	570 ft. (174 m)	333 ft. (100 m)	-138 ft. (-42 m)
Thickness of weathered zone	----	----	----
Interval described	403 ft. (123 m)	519 ft. (158 m)	1079 ft. (329)
Rock type	granodiorite gneiss	foliated diorite	cataclastic gneiss
Grain size	medium to coarse	medium	fine to coarse
Fabric	gneissic-weakly granulated	allotriomorphic granular-weakly foliated	cataclastic-gneissic
Mineralogy (In percentages or order of abundance)	quartz oligoclase alkalic feldspar chlorite calcite muscovite hematite	andesine, 63 biotite 12 chlorite 5 hornblende, 5 quartz, 4 orthoclase, 4 muscovite, 2 magnetite, 1 epidote, 1 sphene, tr. apatite, tr.	quartz microcline perthite calcic oligoclase hornblende biotite muscovite magnetite zircon calcite
Total mafics	----	23%	----
Total SiO_2	64.2%	55.7%	----
Total Fe + MgO	6.2%	15.5%	----
K_2O/Na_2O	0.6	0.5	----

TABLE 1--Continued

Well Number	16-2	17	18
Landowner	Lindholm	Kilichowski	Schuster
Well location	14-153N-54W	9-155N-52W	8-156N-51W
County, State	Grand Forks, ND	Walsh, ND	Walsh, ND
Depth to top of Precambrian	1079 ft. (329 m)	784 ft. (239 m)	644 ft. (196 m)
Elevation of top of Precambrian	-138 ft. (-42 m)	38 ft. (12 m)	161 ft. (49 m)
Thickness of weathered zone	----	----	----
Interval described	1087-1091 ft. (331-333 m)	791 ft. (241 m)	651 ft. (198 m)
Rock type	granodiorite gneiss	quartz monzonite gneiss	granodiorite gneiss
Grain size	fine to medium	medium to coarse	medium
Fabric	gneissic	gneissic	gneissic
Mineralogy (in percentages or order of abundance)	quartz calcic oligoclase hornblende biotite muscovite magnetite zircon calcite	quartz microcline biotite apatite calcite chlorite	quartz, 34 oligoclase, 25 antiperthite, 16 biotite, 15 epidote, 5 microcline, 4 hornblende, 2 sphene, 1 apatite, tr. zircon, tr. pyrite, tr.
Total mafics	----	----	18%
Total SiO_2	57.8%	----	67.6%
Total Fe + MgO	11.6%	----	6.6%
K_2O/Na_2O	0.5	----	0.4

TABLE 1--Continued

Well Number	19AB	23	24
Landowner	Bjorneby	Erickson	Newton
Well location	30-158N-54W	6-131N-46W	21-134N-44W
County, State	Walsh, ND	Wilkin, MN	Ottertail, MN
Depth to top of Precambrian	1291 ft. (393 m)	304 ft. (93 m)	457 ft. (140 m)
Elevation of top of Precambrian	-389 ft. (-120 m)	666 ft. (203 m)	743 ft. (225 m)
Thickness of weathered zone	----	93 ft. (28 m)	167 ft. (51 m)
Interval described	1291 ft. (393 m)	414 ft. (126 m)	636 ft. (194 m)
Rock type	granodiorite	trondhjemite	quartz monzonite
Grain size	medium to coarse	fine to medium	medium
Fabric	gneissic	hypidiomorphic granular	allotriomorphic granular
Mineralogy (In percentages or order of abundance)	quartz 32 antiperthite, 25 oligoclase, 21 biotite 9 microcline, 6 epidote, 3 muscovite, 2 sphene, tr.	oligoclase, 54 quartz, 37 microcline microperthite, 4 biotite, 3 magnetite, tr. hornblende, tr. muscovite, tr. epidote, tr. apatite, tr. sphene, tr. zircon, tr.	microcline 37 perthite, oligoclase, 31 quartz, 22 biotite, 4 chlorite, 2 myrmekite, 2 calcite, 1 opaques, tr. apatite, tr. zircon, tr.
Total mafics	9%	3%	6%
Total SiO_2	70.1%	68.9%	70.5%
Total Fe + MgO	4.8%	2.3%	2.9%
K_2O/Na_2O	0.4	0.2	1.2

TABLE 1—Continued

Well Number	25A	26	27
Landowner	Meyers	Hanson	Novacek
Well location	21-140N-44W	15-145N-47W	11-152N-49W
County, State	Clay, MN	Norman, MN	Polk, MN
Depth to top of Precambrian	457 ft. (140 m)	309 ft. (94 m)	299 ft. (91 m)
Elevation of top of Precambrian	778 ft. (237 m)	572 ft. (174 m)	532 ft. (162 m)
Thickness of weathered zone	----	78 ft. (24 m)	----
Interval described	486 ft. (148 m)	392 ft. (120 m)	307 ft. (94 m)
Rock type	quartz monzonite	quartz monzonite	tonalite gneiss
Grain size	fine	fine to medium	medium
Fabric	hypidiomorphic granular	allotriomorphic granular	gneissic
Mineralogy (In percentages or order of abundance)	oligoclase, 39 quartz, 30 microcline perthite, 23 chlorite, 7 muscovite, tr. calcite, tr. epidote, tr.	microcline, 32 oligoclase, 31 quartz, 22 chlorite, 7 epidote, 5 zircon, tr. sphene, tr. apatite, tr.	calcic oligoclase, 50 quartz, 35 biotite, 6 aegirine-augite, 3 chlorite, 2 muscovite, 1 hematite, tr. magnetite, tr. epidote, tr. zircon, tr.
Total mafics	7%	7%	11%
Total SiO_2	68.9%	66.0%	70.0%
Total Fe + MgO	3.9%	5.0%	5.9%
K_2O/Na_2O	1.0	0.3	0.3

TABLE 1--Continued

Well Number	28	29	30
Landowner	Scheflo	Waage	Walz
Well location	10-150N-44W	32-160N-42W	23-158N-47W
County, State	Red Lake, MN	Roseau, MN	Marshall, MN
Depth to top of Precambrian	378 ft. (115 m)	248 ft. (76 m)	362 ft. (110 m)
Elevation of top of Precambrian	673 ft. (205 m)	864 ft. (263 m)	544 ft. (166 m)
Thickness of weathered zone	----	44 ft. (13 m)	----
Interval described	408 ft. (125 m)	334 ft. (102 m)	383 ft. (117 m)
Rock type	phyllite*	cataclastic felsic tuff*	granodiorite gneiss
Grain size	medium	medium	medium
Fabric	schistose	cataclastic-foliated	gneissic-allotriomorphic granular
Mineralogy (In percentages or order of abundance)	quartz muscovite calcite magnetite hematite	oligoclase quartz epidote chlorite pyrite	calcic oligoclase, 50 quartz, 31 biotite, 11 hornblende, 5 epidote, 2 opaques, tr. apatite, tr. zircon, tr.
Total mafics	----	----	16%
Total SiO_2	69.7%	76.1%	61.0%
Total Fe + MgO	23.8%	1.0%	11.3%
K_2O/Na_2O	29.3	0.6	0.5

TABLE 1--Continued

Well Number	31A		
Landowner	Dierks		
Well location	34-125N-44W		
County, State	Stevens, MN		
Depth to top of Precambrian	224 ft. (68 m)		
Elevation of top or Precambrian	901 ft. (275 m)		
Thickness of weathered zone	120 ft. (37 m)		
Interval described	346 ft. (105 m)		
Rock type	quartz monzonite		
Grain size	fine to medium		
Fabric	allotriomorphic granular		
Mineralogy (In percentages or order of abundance)	quartz, 32		muscovite, 3
	sodic oligoclase, 32		biotite, 1
	microcline perthite, 31		chlorite, 1
			zircon tr.
			opaques, tr.
Total mafics	2%		
Total SiO_2	74.5%		
Total Fe + MgO	0.7%		
K_2O/Na_2O	1.2		

* = mapped as schist

[1]Weathered material appears to be derived from this rock type.

[2]Rock is migmatitic, weathered material consists of alternating layers light colored clayey material which is weathered granitic material, and darker clay which is weathered schist. The dark material predominates, so well 8 is mapped with the schists.

clearly volcanic rock encountered (Karner et al. 1980).

An extension of the Vermillion fault, described by Sims (1972) is shown as proposed by Okland (1978), based on interpretation of magnetic work. The northeast trending shear zone is proposed on the basis of cataclastic textures in rocks recovered from three geographically aligned wells, namely RRVD wells 16 and 29, and NDGS well 334 to the west of the study area (Ray and Karner 1979).

Previous Studies of Weathering

General

Goldich (1938) was one of the first geologists to make a thorough study of rock weathering. Goldich studied the pre-Cretaceous weathering profile of the Morton Gneiss, along with profiles developed on two diabase bodies and an amphibolite. From chemical and mineralogical trends, he observed that the order of increasing stability of common rock-forming minerals was generally similar to the order of crystallization of minerals from a melt. He found the relative stabilities of the major oxides to be CaO, Na_2O, K_2O, SiO_2, Al_2O_3, from least to most stable.

Work similar to that of Goldich (1938) has been carried out, and his concepts expanded by many workers studying weathering of various rock types under various climatic conditions.

Brock (1943) studied a modern weathering profile developed on granite near Hong Kong. He noted the early loss of calcium and sodium. Potassium was lost in the intermediate stages of weathering, and iron and silica in the final stages. The residuum left from the weathering consisted mainly of quartz, kaolinite, and sericite.

Butler (1953) studied weathered rocks in Cornwall, England, including both granitic rocks and mafic schists. He found kaolinite and illite to be the predominant minerals in all the weathering products studied. Other clay minerals were found scattered, and in minor quantities. Butler found the compositions of the residual clays to be nearer each other than those of the rocks.

Yamasaki et al. (1955) studied a weathered horizon developed on granodiorite in Japan. They observed increased content of Al_2O_3, and Fe_2O_3 with increased weathering, and losses of SiO_2, Na_2O, K_2O, and CaO.

Sand (1956) studied residual kaolins in the Southern Appalachians. The sequence of mineral alteration he observed was compatible with that of Goldich (1938). Sand also observed remnants of feldspars altered to "books" of secondary micas and/or kaolinite. He found that feldspathic rocks high in mica weathered to clays high in kaolinite, and those low in mica weathered to materials high in hydrated halloysite.

Short (1961) studied soil profiles developed on granitic rocks, andesite and basalt. He found that the largest chemical concentration changes occurred across the rock-soil interface, and that the only distinct difference in major element content between the soils of acid and basic parentage was in concentrations of silica and iron.

Harriss and Adams (1966), in a study of weathering of granitic rocks in Oklahoma and Georgia, found:

1. Relative minerals stabilities were (from least to most stable, respectively) were in the order: plagioclase, biotite, alkali feldspar, and quartz.

2. The sharpest physical and chemical contrasts occurred in the transition from weathered rock to soil.

3. Kaolinite was the predominant clay mineral in the Georgia soil profiles. Kaolinite and illite were major constituents of soils developed in the drier Oklahoma climate.

Wolff (1967) studied a mound of weathered quartz monzonite near Baltimore. He reported relative mineral stabilities to be the same as those of Harriss and Adams (1966). He noted little change in bulk chemistry between parent rock and weathered material, with the exceptions of increases in K_2O and H_2O. Halloysite was the major clay mineral in the weathered material.

Clemency (1975) studied a weathering surface developed simultaneously on granite gneiss and amphibolite. He noted preservation of physical differences between the two rock types, and thought this most easily explained by a permeability difference which controlled composition of water which penetrated and altered the rocks.

Meunier and Velde (1979) studied weathering of two-mica granites. Among their findings, they noted that silica was conserved in the initial stages of weathering, and lost in the later stages.

Recently, studies in rock weathering have turned to extensive use of the scanning electron microscope for textural information (Keller 1978a, b; Rodgers and Holland 1979), and studies of the behavior of trace elements during weathering (Nesbitt 1979).

Weathering in Eastern North Dakota and Western Minnesota

Kline (1942) was the first to recognize the existence of residual clay above the basement "granite" (quotes are hers) in the Red River

Valley. She wrote: "Samples show the upper part of the granite to be decomposed to form a soft sticky mass of flaky kaolinite and quartz grains. This decomposed zone may reach a thickness of 200 feet or more in some places."

Kline further noted that this altered zone was not found where the Precambrian is overlain by rocks older than Cretaceous.

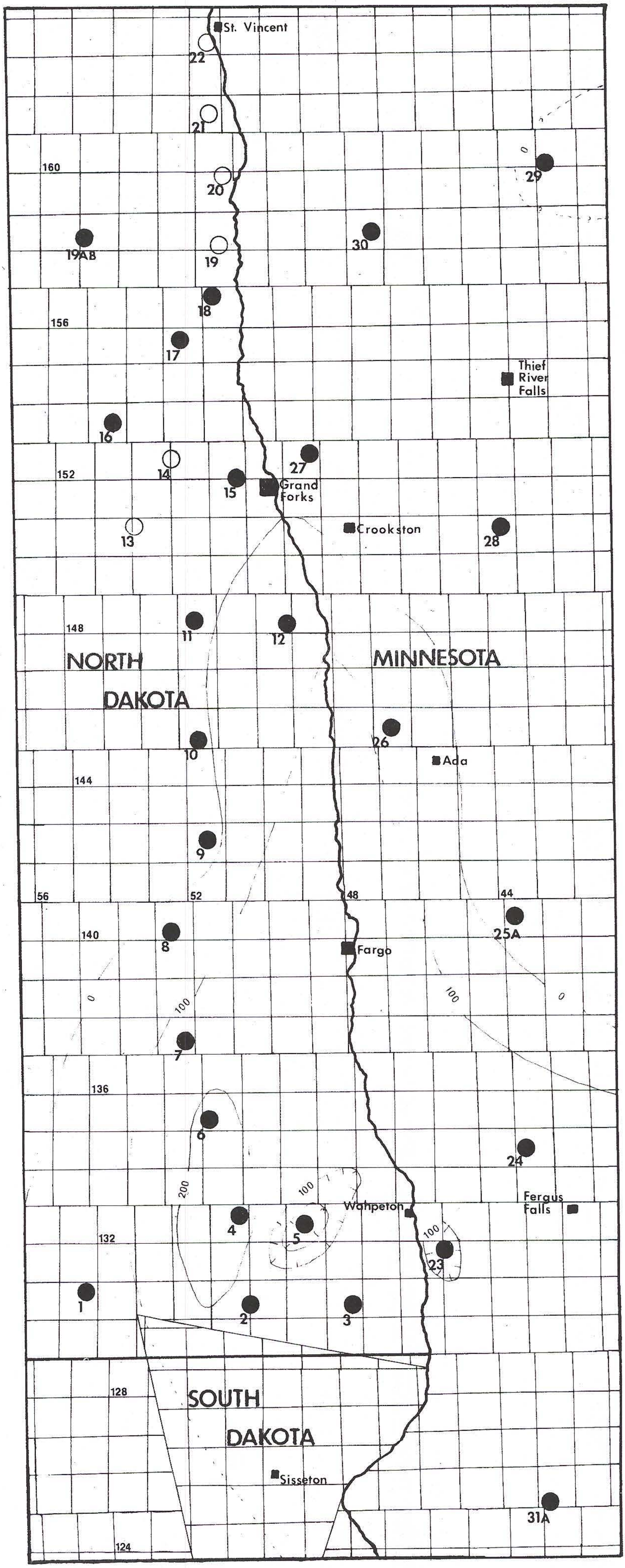
A portion of Goldich's (1938) study concerned the weathering of the Morton Gneiss in the Minnesota River Valley. Recent compilations by Sloan (1964), and Parham (1970; 1972) show that the object of Goldich's investigation is part of a pre-Cretaceous weathering zone which covers most of western Minnesota, including the Red River Valley. The present study extends westward the known boundary of this pre-Cretaceous weathering horizon (Figure 19).

Klausing (1968), Baker (1967), and Bluemle (1967) have mentioned the presence of weathered granite overlying crystalline basement rocks in their studies of eastern North Dakota counties.

The weathering zone is generally restricted to the southern half of the Red River Valley. The edge of the zone forms a southward-opening "V," with its apex below the Grand Forks area. The maximum thickness of over 200 ft. (70 m) is west of Wahpeton, North Dakota. A thinning, to zero is just east of the area of maximum thickness (Figure 4). This is probably a Pleistocene erosional thinning. The Pleistocene section there is unusually thick, and the lowermost part of the section consists of coarse clastics which are interpreted as a meltwater channel deposit (Moore 1978).

Fig. 4. Isopach map of weathered Precambrian in the Red River Valley. Map is highly interpretive, as control is minimal. Contour interval = 100 ft. Modified slightly from Moore (1978).

Fig 4
pg 27



St. Vincent
22
21
160
20
29
19AB
19
30
18
156
17
Thief River Falls
16
27
152
14
15
Grand Forks
Crookston
13
28
148
11
12
NORTH DAKOTA
MINNESOTA
10
26
Ada
144
9
56
52
48
44
140
8
25A
Fargo
0
100
100
0
7
136
6
24
200
100
Wahpeton
Fergus Falls
4
5
100
132
23
1
2
3
128
SOUTH DAKOTA
Sisseton
31A
124

CHEMISTRY AND PETROGRAPHY OF THE WEATHERED ZONE

Procedures

Cores from the Red River Valley Drilling Project are stored in the North Dakota Geological Survey Core and Sample Library, Grand Forks. The project geologists attempted to core the unconformity at the top of the Precambrian, again somewhere in the weathered zone, and again when fresh crystalline rock was penetrated. There are no continuous cores, hence sample spacing is somewhat irregular (Moore 1978).

Samples were selected by beginning at the uppermost section of core which included weathered and/or fresh Precambrian material. If the rock was unweathered, usually only one sample was taken. In cases of cores in which a weathered zone was present, a sample was taken either every 10 ft. (3 m) or whenever the character of the material changed (i.e. color, texture, etc.). The irregular coring intervals led to irregular sample spacing, but with respect to the core recovered, the samples are believed to be representative.

Whole rock chemistry was determined by rapid electron microprobe analysis of small powdered samples. A portion of each sample was crushed in a jaw crusher, then ground to a fine powder, dried in an oven at 110°C for one hour, and loaded into 3/16 in. (.5cm) cylindrical cavities in 1¼ in. (3.2 cm) diameter bakelite holders. The instrument used was a JEOL 35 scanning electron microscope with an energy dispersive x-ray fluorescence detector. The fluorescence spectra were processed by a

Tracer Northern XML fitting program and the matrix correction program of Bence and Albee (1968) using USGS standard rock powders. These chemical analyses are reported on a normalized, oxygen-free basis (Karner, personal communication).

X-ray diffraction analysis was carried out on selected samples using the glycolated pellet technique of Karner and Wosick (1975). The pellets were x-rayed using Cu K-alpha radiation in a Philips high angle diffractometer. Minerals were identified using descriptions and charts in Carroll (1970a), and ASTM powder data. Rock fabric was studied using petrographic thin sections made by impregnating friable samples following the techniques of Hutchison (1974). Thin sections were observed by optical and scanning electron microscope techniques. Broken surfaces of samples were observed through scanning electron microscope techniques.

For the purposes of this study, I have divided the basement rocks of the Red River Valley into terranes of granitic rocks and intermediate to mafic schists (Figure 3), following the work of Muehlberger et al. (1967).

In describing the weathered material, I have used the subjective terms fresh, slightly weathered, moderately weathered, and highly weathered. Table 2 delineates the criteria used to divide the material.

Granitic Rocks

Fresh Granitic Rock

The "granitic" rocks range in composition from quartz diorite to granite, with trondjhemite being the most abundant rock. Most of the granitic rocks are gneissic, with the foliation generally dipping

TABLE 2

CHARACTERISTICS OF WEATHERED UNITS

Degree of alteration	Original fabric present	Degree of plagioclase alteration	Degree of alkali feldspar alteration	Degree of biotite alteration	Proportion of clay minerals	Maximum thickness
Fresh rock	yes	slight-none	none	slight	none	?
Slightly weathered	yes	moderate	slight-none	moderate-severe	none	50-60 ft. (20 m)
Moderately weathered	no	severe	moderate-severe	*	<10%	100 ft. (30 m)
Severely weathered	no	*	*	*	>50%	50-60 ft. (20 m)

*Mineral is not found, apparently completely destroyed.

(assuming the core was vertical) about 45±15°. They typically contain 65-70% SiO_2. Generally the ratio K_2O/Na_2O is low, (0.3-0.6), as is typical of Archaean granitic rocks. Quartz monzonites in the southern part of the area have higher K_2O/Na_2O ratios, and may be younger than the rocks to the north (Karner et al. 1980). The modal composition of these rocks varies, but they are generally composed of plagioclase (30-60%), quartz (20-35%), muscovite, biotite, chlorite, hornblende (<5% of each), ± alkali feldspar (0-30%). The plagioclase is generally sodic. The alkali feldspar is most often microcline perthite.

Slightly Weathered Granitic Rock

In the early stages of weathering, the granitic rocks retain vestiges of their original fabric, on both macroscopic and microscopic scales. Altered layered gneissic rocks often show remnants of original layering (Figure 5). The dark zones in the gneissic rocks generally contain amphibole and/or biotite, which are usually altered to chlorite in the weathered material.

In thin section, chlorite can be seen to replace biotite and/or amphibole, and subhedral plagioclase crystals often have sericitic rims (Figure 6). Clay minerals are not detected through use of x-ray diffraction at this stage.

Relative losses of a large amount of calcium and magnesium and a lesser decrease in sodium content are typical of slightly to moderately weathered granitic material. The relative concentrations of these elements continue to decline in the zone of more severe weathering (Figures 7, 8, Table 3).

Fig. 5. Photographs of fresh granitic gneiss and slightly-moderately weathered quartz monzonite gneiss showing preservation of gneissic structure.

5a. Fresh granitic gneiss.
Well 19A, 1297 ft. (400 m),
$2\frac{1}{2}$ in. (6.35 cm) diameter core.

5b. Slightly-moderately weathered quartz monzonite gneiss showing preservation of gneissic structure.
Well 26, 390 ft. (120 m),
$2\frac{1}{2}$ in. (6.35 cm) diameter core.

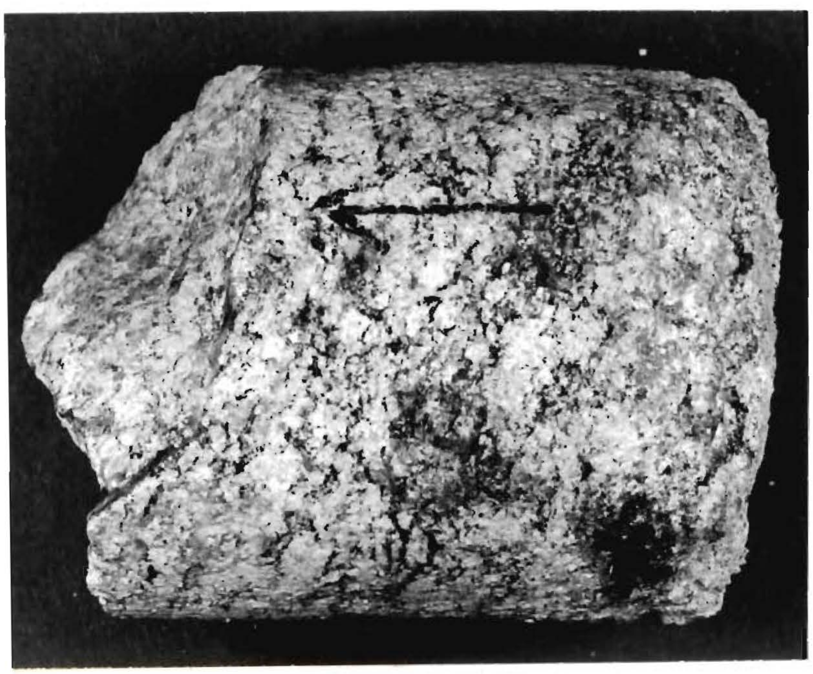


Fig. 6. Photomicrograph of thin section of slightly weathered granodiorite from well 3, 450 ft. (140 m). Plagioclase grain showing sericitized edges. Dark bands cutting across twinning planes are also sericite. Crossed polars, 60 X.

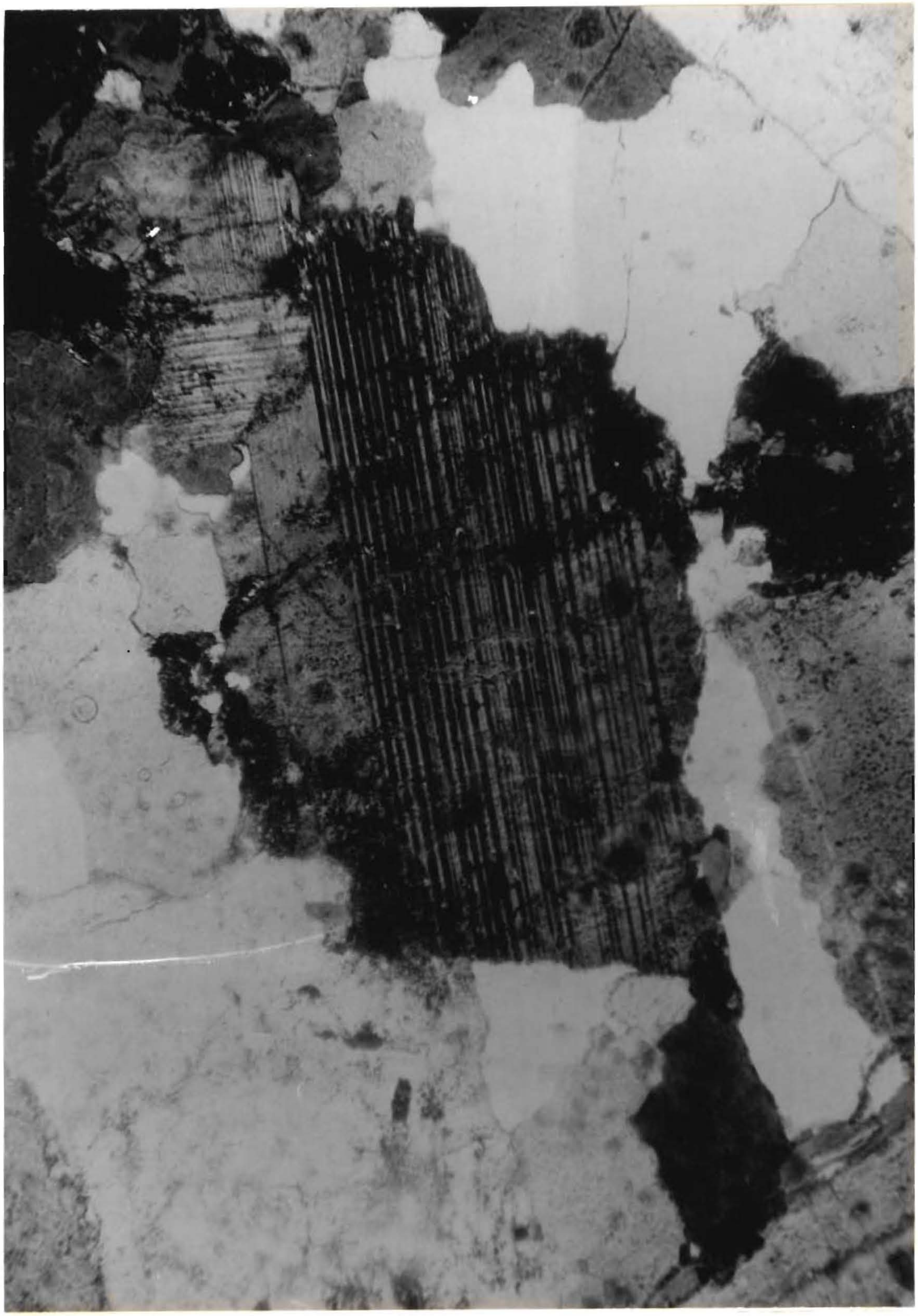
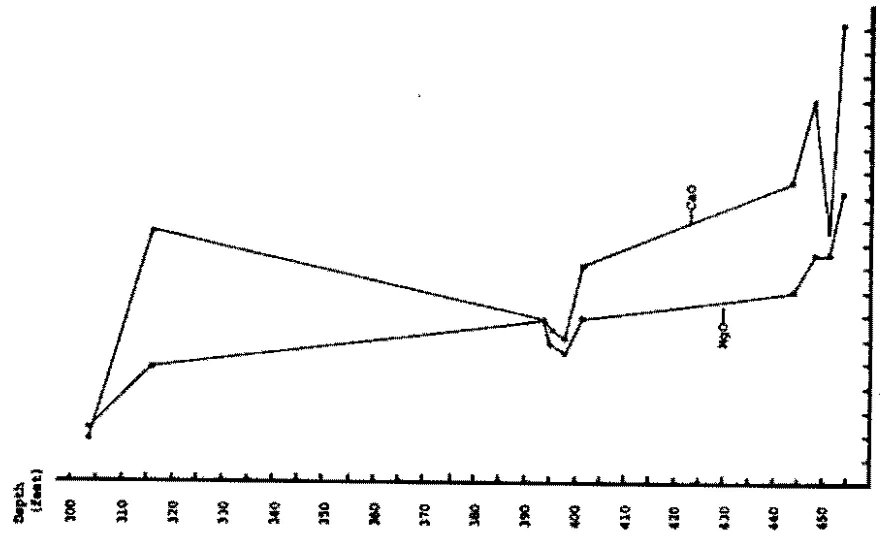


Fig. 7. Plot of concentrations of CaO and MgO versus depth, well 3.

Fig. 8. Plot of concentrations of Na_2O and K_2O versus depth, well 3.


Depth (feet)
300
310
320
330
340
350
360
370
380
390
400
410
420
430
440
450
1
2
3
4
Concentration
CaO
MgO

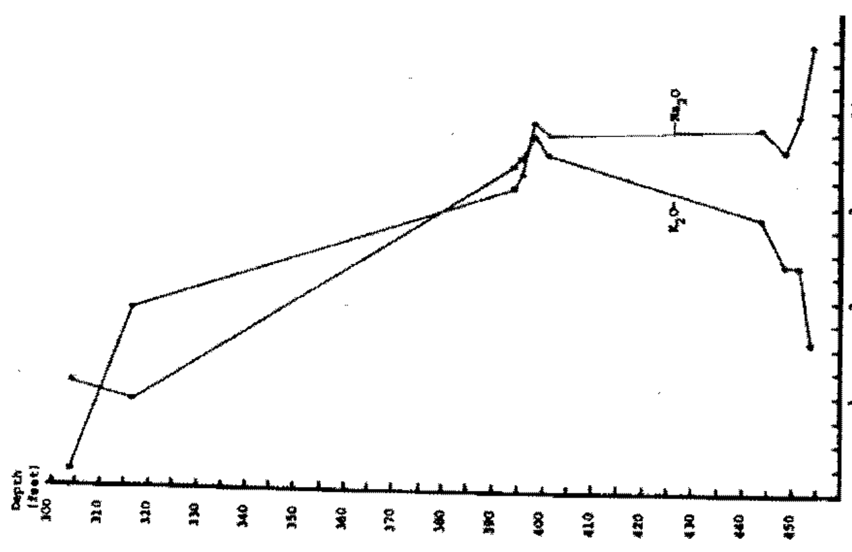

Depth (feet)
300
310
320
330
340
350
360
370
380
390
400
410
420
430
440
450
1
2
3
4
Concentration
K_2O
Na_2O

Table 3. Chemical analyses of Red River Valley rocks and weathering products. Samples are numbered using a multi-digit hyphenated code. The number preceding the hyphen refers to the well number, the numbers following the hyphen are sample numbers within each well. Analyses are reported as oxide percentages.

Sample no.	Depth, ft. (m)	Elev., ft. (m)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	ClO	SO_3
1-1	843 (257)	427 (130)	39.70	20.88	31.54	2.04	3.07	0.00	0.11	0.95	0.42	1.27	0.00	0.01
1-2	848 (259)	422 (129)	50.92	30.55	11.73	1.32	2.23	0.92	0.40	1.61	0.00	0.29	0.00	0.01
1-3	852 (260)	418 (127)	51.54	29.57	7.24	1.92	6.13	0.68	1.61	1.09	0.08	0.07	0.00	0.01
1-4	858 (262)	412 (126)	44.53	29.30	20.60	1.02	1.61	0.18	0.21	1.60	0.18	0.82	0.00	0.01
1-5	905 (276)	365 (111)	64.01	19.84	6.21	1.34	4.23	2.82	0.82	0.72	0.00	0.00	0.00	0.00
1-6	912 (278)	358 (109)	50.04	21.64	14.62	6.30	2.35	1.40	2.27	0.93	0.29	0.15	0.00	0.01
1-7	917 (280)	353 (108)	54.97	18.20	11.14	2.12	7.65	3.48	0.81	1.20	0.10	0.34	0.00	0.01
1-8	924 (282)	346 (105)	64.90	14.60	7.60	2.30	4.26	3.74	0.53	1.84	0.23	0.00	0.00	0.00

TABLE 3--Continued

Sample no.	Depth, ft. (m)	Elev., ft. (m)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	ClO	SO_3
3-1	304 (93)	686 (209)	63.04	28.54	4.81	0.54	0.42	0.15	1.08	1.15	0.09	0.02	0.00	0.00
3-1.5	316 (96)	674 (205)	58.25	27.21	6.82	1.30	2.56	1.84	0.89	0.95	0.15	0.00	0.00	0.01
3-2	394 (120)	596 (182)	66.25	16.97	5.77	1.71	1.71	3.15	3.39	0.78	0.17	0.00	0.02	0.00
3-3	396 (121)	594 (181)	67.17	17.21	4.94	1.42	1.59	3.34	3.45	0.60	0.17	0.00	0.04	0.00
3-4	398 (121)	592 (180)	66.78	17.49	4.62	1.35	1.49	3.81	3.70	0.70	0.00	0.00	0.00	0.00
3-5	402 (123)	588 (179)	68.74	16.00	3.78	1.35	2.24	3.72	3.50	0.54	0.00	0.00	0.00	0.07
3-6	444 (135)	546 (166)	65.60	15.44	6.39	1.96	3.14	3.80	2.82	0.61	0.09	0.09	0.00	0.00
3-7	449 (137)	541 (165)	62.70	16.20	8.22	2.38	3.96	3.56	2.35	0.80	0.08	0.10	0.05	0.18
3-8	452 (138)	538 (164)	64.60	15.46	7.84	2.39	2.61	3.95	2.33	0.54	0.17	0.00	0.06	0.00

TABLE 3--Continued

Sample no.	Depth, ft. (m)	Elev., ft. (m)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	ClO	SO_3
4-3	724 (221)	334 (102)	62.19	23.54	4.25	1.22	0.11	1.99	6.20	0.40	0.00	0.11	0.00	0.00
4-4	731 (223)	327 (100)	74.26	15.43	3.87	0.50	0.74	0.46	4.40	0.35	0.00	0.00	0.00	0.00
5-2*	382 (116)	606 (185)	72.67	14.71	2.18	0.40	1.12	3.54	4.84	0.24	0.10	0.00	0.00	0.00
6-2	427 (130)	638 (194)	52.58	38.30	6.20	0.48	0.54	1.20	0.18	0.49	0.00	0.00	0.00	0.02
6-3	436 (133)	629 (192)	55.30	35.34	5.85	0.42	0.29	0.32	0.28	2.11	0.00	0.09	0.00	0.02
6-4	626 (191)	439 (134)	52.50	18.82	13.74	8.70	0.70	3.23	1.42	0.89	0.00	0.00	0.00	0.00
7-1	580 (177)	468 (143)	57.54	35.42	2.87	0.00	0.30	0.66	1.67	1.48	0.00	0.10	0.00	0.00
7-2	721 (220)	327 (100)	64.14	17.50	4.43	1.65	3.12	3.99	3.92	1.13	0.14	0.00	0.00	0.00
7-3	724 (221)	324 (98)	54.49	16.65	12.97	3.92	3.35	3.86	2.70	1.70	0.36	0.00	0.00	0.00

TABLE 3--Continued

Sample no.	Depth, ft. (m)	Elev., ft. (m)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	F_2O_5	MnO	ClO	SO_3
8-1	528 (161)	469 (143)	64.96	21.43	2.81	0.83	1.49	3.55	4.37	0.58	0.00	0.00	0.00	0.00
8-2	533 (162)	464 (141)	59.04	21.13	12.35	3.07	1.12	1.26	1.42	0.60	0.00	0.00	0.00	0.00
8-3	603 (184)	394 (120)	53.43	18.67	13.24	4.01	3.38	3.12	2.53	1.53	0.10	0.00	0.00	0.00
8-4	618 (188)	379 (116)	71.70	11.55	1.56	0.72	9.78	1.00	3.32	0.00	0.00	0.34	0.00	0.01
9-1	593 (181)	427 (130)	69.78	16.24	2.52	0.67	1.81	4.61	4.08	0.27	0.00	0.00	0.00	0.00
9-2	600 (183)	420 (128)	70.89	15.93	2.12	0.64	1.82	4.81	3.34	0.35	0.00	0.09	0.00	0.00
10-2*	557 (170)	413 (126)	41.27	14.92	19.20	13.08	9.20	0.92	0.05	0.96	0.08	0.16	0.00	0.11
11-1	681 (208)	302 (92)	61.80	23.88	1.56	1.46	0.41	0.51	10.18	0.21	0.00	0.00	0.00	0.00

TABLE 3--Continued

Sample no.	Depth, ft. (m)	Elev., ft. (m)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	ClO	SO_3
12-1	396 (121)	476 (145)	61.35	20.29	5.68	1.75	3.58	3.45	3.79	0.41	0.11	0.21	0.00	0.00
12-2	412 (126)	460 (140)	65.64	16.73	3.66	0.95	5.87	3.84	2.58	0.63	0.00	0.10	0.00	0.00
15-1	506 (154)	334 (102)	54.09	23.70	8.42	3.40	3.38	0.66	5.50	0.77	0.07	0.00	0.00	0.01
15-2	512 (156)	328 (100)	60.10	15.91	7.44	4.34	5.00	4.25	1.97	0.68	0.15	0.13	0.00	0.01
15-3	520 (158)	320 (98)	54.67	15.87	11.46	7.08	3.16	5.29	1.07	0.85	0.57	0.00	0.00	0.00
16-3	1090 (332)	-149 (-45)	63.09	16.02	6.87	3.29	4.00	4.62	0.98	0.94	0.21	0.00	0.00	0.00
17-2*	557 (170)	265 (81)	54.94	14.44	10.90	2.70	7.03	0.19	8.78	0.65	0.12	0.17	0.00	0.00
18-1*	653 (199)	152 (46)	67.60	14.98	4.79	1.77	2.88	4.83	1.92	0.64	0.23	0.11	0.00	0.19
19A-2	1299 (396)	-397 (-121)	65.55	14.69	7.73	1.83	2.28	3.31	3.53	0.75	0.14	0.19	0.00	0.00

TABLE 3--Continued

Sample no.	Depth, ft. (m)	Elev., ft. (m)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	F_2O_5	MnO	ClO	SO_3
23-1	310 (94)	660 (201)	57.17	35.12	2.32	0.45	0.76	2.10	0.68	1.31	0.09	0.00	0.00	0.00
23-2	405 (123)	565 (172)	69.61	16.40	2.95	0.87	2.83	5.41	1.48	0.36	0.00	0.14	0.00	0.00
24-1	529 (161)	671 (205)	68.40	18.94	2.93	1.13	1.34	2.37	4.45	0.46	0.00	0.00	0.00	0.00
24-2	546 (166)	654 (199)	67.12	17.85	3.69	1.74	0.94	2.63	5.42	0.50	0.00	0.10	0.00	0.00
24-3	624 (190)	576 (176)	64.68	21.19	2.84	1.03	1.87	3.03	4.71	0.64	0.00	0.00	0.00	0.00
25-1	481 (147)	754 (230)	66.22	18.24	3.78	1.07	0.37	4.34	4.73	1.03	0.00	0.00	0.00	0.00
26-1	373 (113)	508 (155)	66.28	18.63	3.70	1.82	1.29	7.44	1.31	0.47	0.00	0.00	0.00	0.00
26-2	393 (120)	488 (149)	67.02	17.90	2.46	1.33	3.26	5.67	2.04	0.32	0.00	0.00	0.00	0.00
27-1	296 (90)	535 (163)	48.04	13.02	22.93	3.70	4.90	1.87	2.64	1.42	0.30	0.27	0.00	0.01

TABLE 3--Continued

Sample no.	Depth, ft. (m)	Elev., ft. (m)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	F_2O_5	MnO	ClO	SO_3
27-2	305 (93)	526 (160)	65.37	19.49	2.07	0.93	4.51	6.46	1.02	0.14	0.00	0.00	0.00	0.00
27-3	308 (94)	523 (159)	57.16	17.26	8.12	5.31	4.36	4.18	2.63	0.88	0.00	0.12	0.00	0.00
27-4	319 (97)	512 (156)	61.45	15.95	7.02	3.83	4.69	4.26	1.72	0.73	0.23	0.13	0.00	0.00
28-1	383 (117)	668 (204)	61.47	24.23	6.63	0.13	0.44	0.37	6.25	0.50	0.00	0.00	0.00	0.00
29-1	261 (80)	851 (259)	66.17	17.78	2.50	1.76	0.14	4.62	6.86	0.15	0.00	0.00	0.00	0.01
29-2	323 (98)	789 (240)	75.88	12.10	2.63	1.39	0.17	3.48	4.17	0.17	0.00	0.00	0.00	0.00
29-3	330 (101)	782 (238)	70.66	15.37	1.42	0.93	0.00	2.98	8.53	0.10	0.00	0.00	0.00	0.00
30-1	370 (113)	755 (230)	57.10	16.61	9.77	3.24	5.50	3.65	1.97	1.74	0.25	0.18	0.00	0.00

*From Karner et al. (in preparation).

Moderately Weathered Granitic Rock

Higher in the section, the altered material loses all traces of original structure. The material resembles a very coarse, clayey sandstone. It is usually a pale green or gray, and consists of highly altered feldspars, and fairly fresh, angular quartz grains in a clay matrix.

Plagioclase is further altered until it is completely changed to sericite or clay. Alkali feldspars, if present in the original rock, show altered rims. Quartz grains are relatively unaltered and angular.

X-ray diffraction shows small, broad 7-Å peaks, indicating the presence of kaolin-group minerals. Kaolin minerals, sometimes as pseudomorphs after feldspar, can be observed through scanning electron microscopy (Figure 9).

Potassium concentrations decrease in the moderately weathered zone, as alkali feldspar and muscovite break down. Magnesium, sodium, and calcium continue to decrease in abundance (Figures 7, 8, Table 3).

Severely Weathered Granitic Rock

The upper, most altered section of the weathering zone is a structureless, massive, fine-grained greenish-white clay, with suspended angular quartz grains. The quartz grains show some sign of alteration, but are generally angular. A few flakes of authigenic? muscovite occur in this material. All traces of feldspar are generally absent.

Kaolinite is the predominant mineral in the upper highly weathered part of the profile. Kaolinite increases in both abundance and degree of crystallinity. The degree of crystallinity is measured

Fig. 9. Scanning electron micrograph of kaolin aggregate pseudomorphous after feldspar. Well 7, 580 ft. (180 m). Bar scale = 10 micrometers.


0013
10.0U
UND80

by the peak height/width ratio of the principal x-ray diffraction peak of clay minerals (Carroll 1970a). Figure 10 shows changes in the 7-Å kaolinite peak with increased weathering in a granitic horizon.

Through the scanning electron microscope, kaolinite is seen to occur in flake form (Figure 11). Pseudomorphs after feldspar are seldom found.

Alumina concentrations show a relative increase in the upper part of the profile. This alumina increase is not an actual addition of alumina, but a relative increase due to removal of other, more chemically mobile oxides. Silica concentrations decrease. Concentrations of other major oxides continue to decrease, in some cases to less than one per cent (Figure 12, Table 3).

Schists

Fresh Schist

The composition of rocks mapped as intermediate to mafic schists vary more than that of the granitic rocks. Most of these rocks are chlorite schists. The apparent dip of the schistosity is approximately 60-90°. Mineralogically, the schists consist of sub-equal parts of plagioclase, quartz, and chlorite or chloritized biotite. Also present are amphibole (up to 10%), muscovite (up to 5%), and a variety of accessory minerals, including hematite, magnetite, pyrite, and garnet. The chlorite schists are probably metamorphosed fine-grained clastic sedimentary or volcaniclastic rocks.

Core from well 10, a metamorphosed basalt composed of amphibole and chlorite with pyrite-bearing quartz veinlets, is the only material which is clearly of volcanic origin.

Fig. 10. X-ray diffractograms of samples from well 3 using Cu K alpha radiation.

3-1.5 - highly weathered material

3-4 - moderately weathered

3-8 - fresh granodiorite

K = kaolinite
M = muscovite/biotite
P = Plagioclase feldspar
Q = Quartz
A = Alkali Feldspar
Si = Silicon metal added to powder as an internal standard

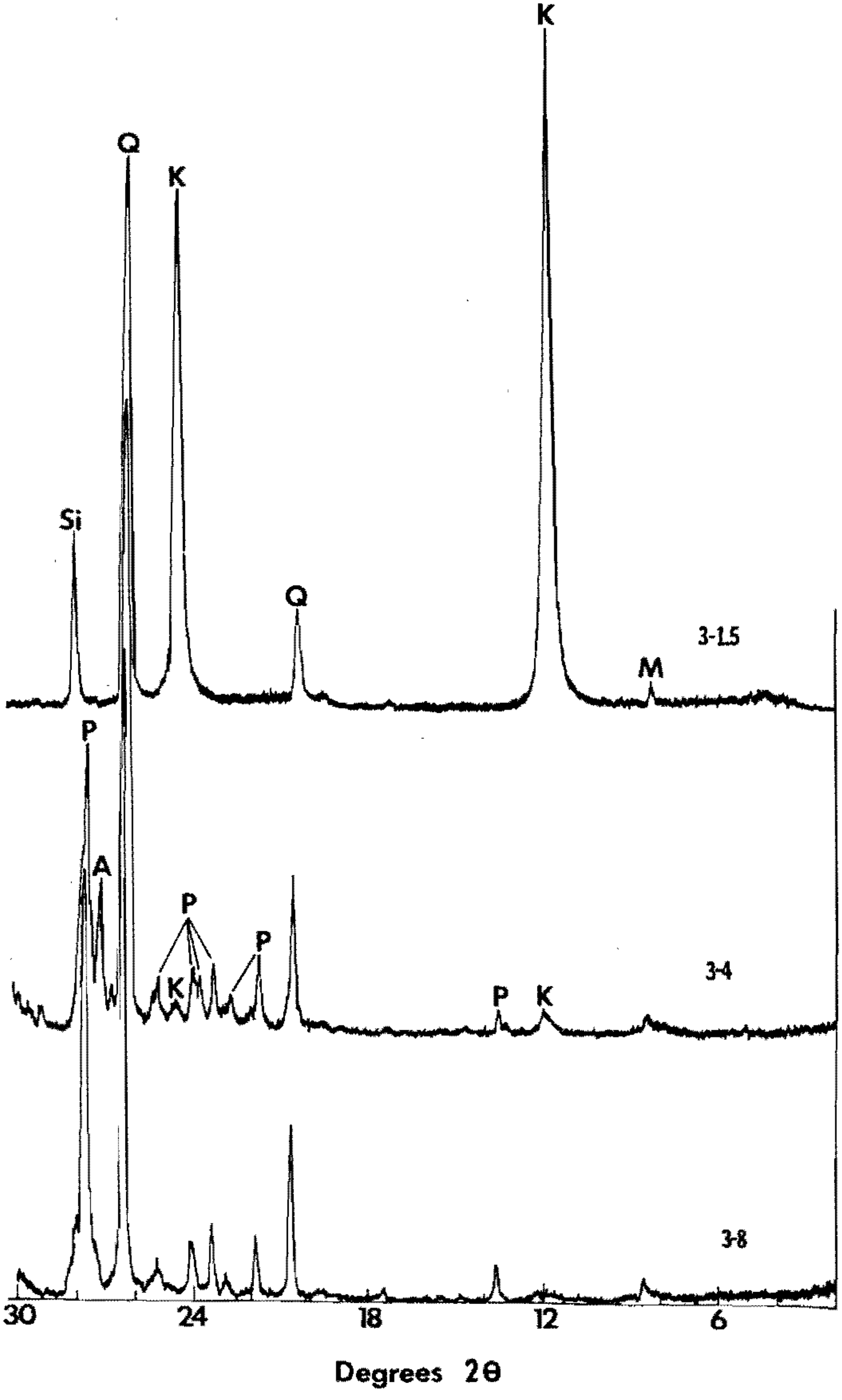

K
Q
K
Si
Q
3-1.5
M
P
A
P
P
K
P
K
3-4
3-8
30
24
18
12
6
Degrees 2θ

Fig. 11. Scanning electron micrograph showing quartz grain in center, surrounded by flakes of kaolinite. Well 3, 300 ft. (100 m). Bar scale = 10 micrometers.

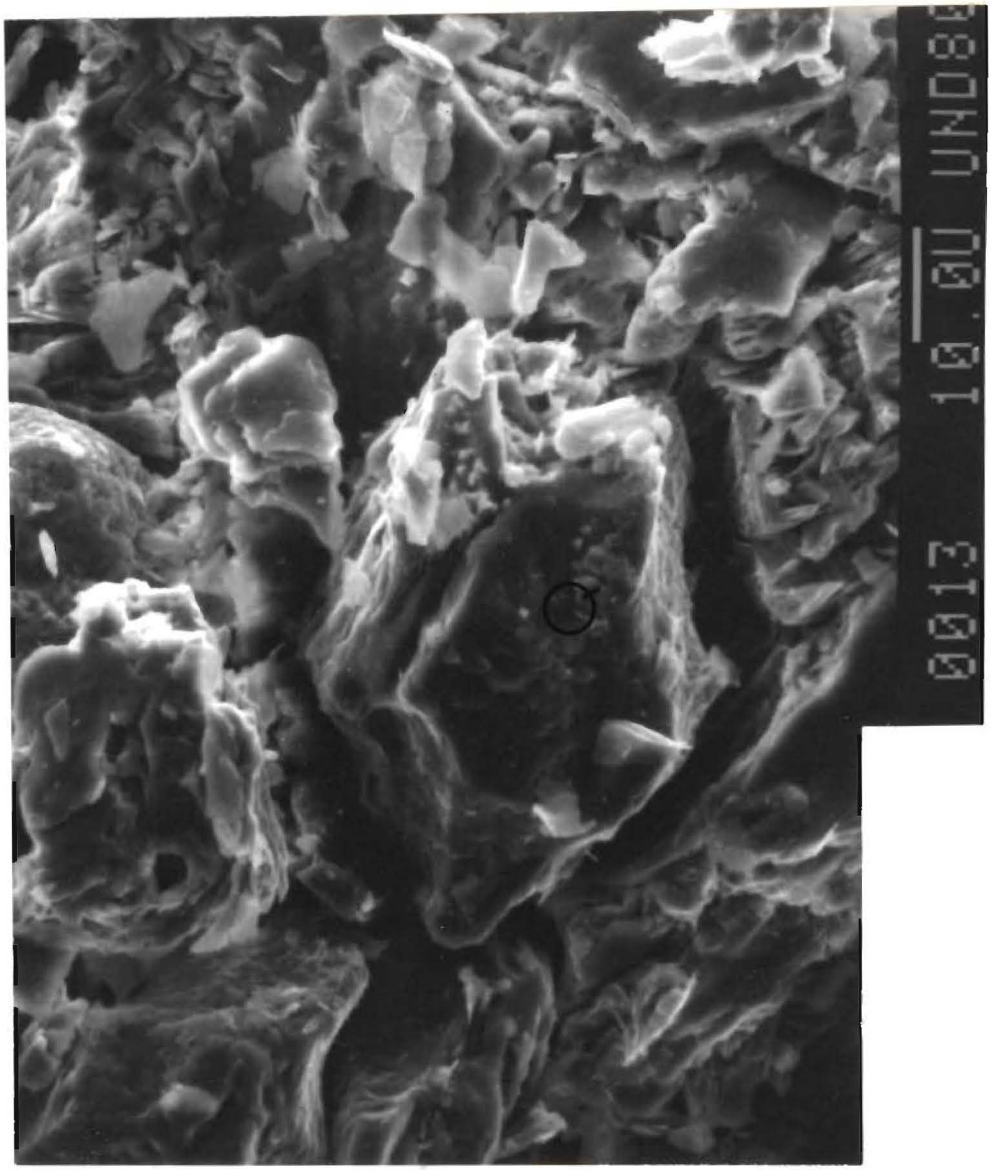
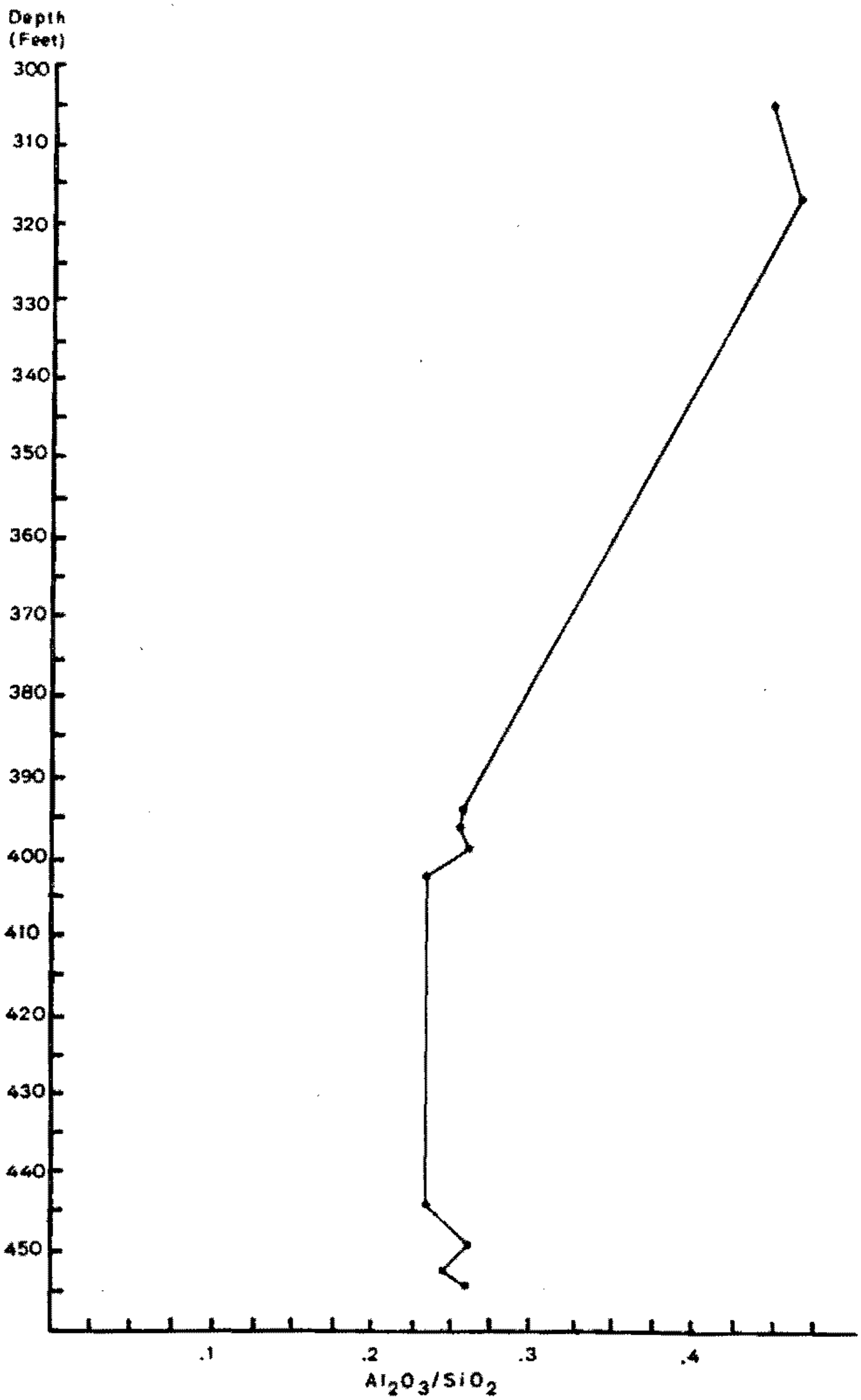

0013 10.0U

Fig. 12. Plot of Al_2O_3/ SiO_2 versus depth, well 3.


Depth
(Feet)
300
310
320
330
340
350
360
370
380
390
400
410
420
430
440
450
.1
.2
.3
.4
Al_2O_3/SiO_2

Material recovered from well 29 may be a sheared felsic tuff, composed of sub-equal parts of quartz, plagioclase, and alkali feldspar, with minor biotite, chlorite, and disseminated pyrite.

Material from well 1 may be a meta-volcanic breccia or tuff. However, this material is confined to the lower few feet of the core. The rest is chlorite schist.

Slightly Weathered Schist

Metamorphic textures and structures of chlorite schist disappear with only a slight degree of weathering. Chemical trends are grossly similar to those of the granitic rocks (Table 3), but there is greater variation, likely due to the variations in composition of the original sediments.

Moderately Weathered Schist

In moderately weathered schist, mineralogic inhomogeneity is sometimes manifested in a layering of fairly solid rock alternating with more altered rock. The layers differ in quartz content, the layers with more quartz being more altered (Figure 13). At this stage, the rock is a green kaolinitic, sandy material, which lacks structure.

Severely Weathered Schist

The upper, most weathered parts of the profiles developed on schist consist of white to greenish kaolinite with "floating" quartz grains and spherical siderite concretions of approximately 1mm - 1cm diameter (Figure 14). The deepest weathering profile is capped by a 3 ft. (1m) thick layer of pisolitic kaolinite (Figures 15, 16). The

Fig. 13. Photograph of core recovered from well 2, 823-838 ft. (250-255 m), showing fresh quartz-chlorite schist (F) alternating with with layers of relatively quartz-poor, more weathered material (W). 2½ in. (6.35 cm) diameter core.

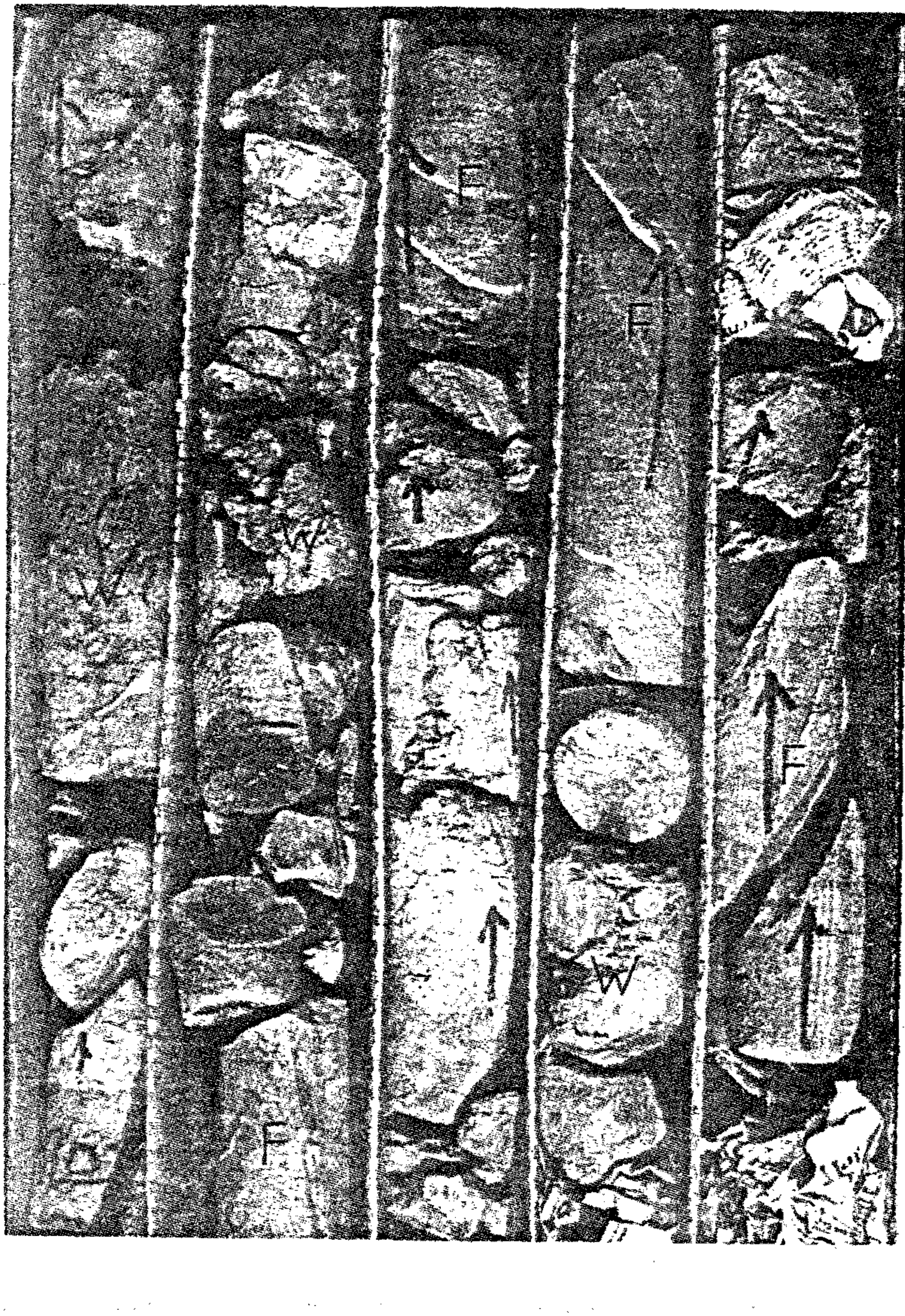

F
F
W
W
F
W
F

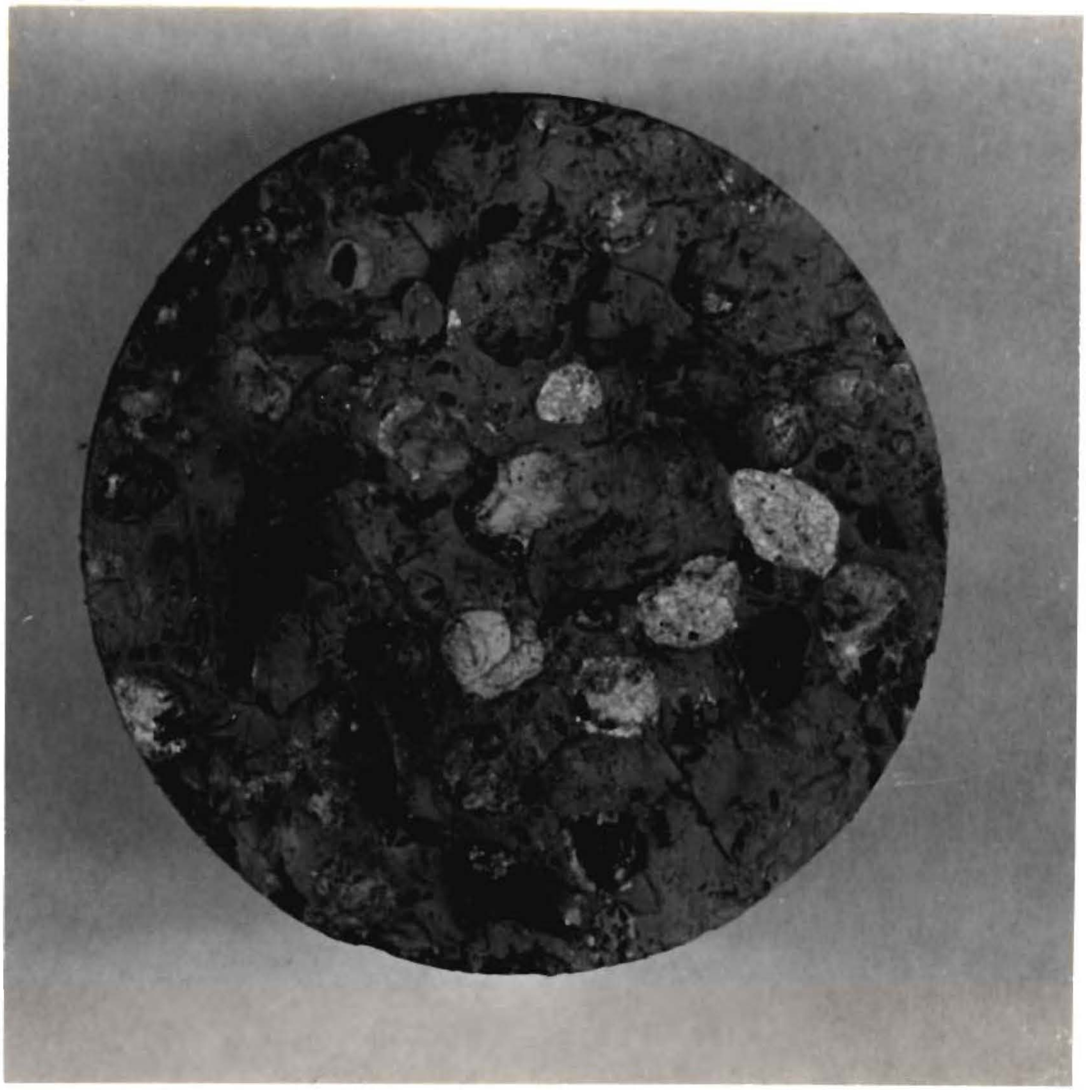
Fig. 14. Clay from upper portion of weathering profile in well 2, 633 ft. (190 m), showing general lack of structure except for siderite nodules (S).


S
S
S
.5
.5
CENTIMETRE

Fig. 15. Photograph of core recovered from well 6, at Precambrian-Cretaceous unconformity. K = organic Cretaceous shale. P = pisolitic kaolinite. C = white, massive kaolinite. Well 6, 424-436 ft. (130-133 m), 2½ in. (6.35 cm) diameter core.


C
C
K
P
C
TOP
K

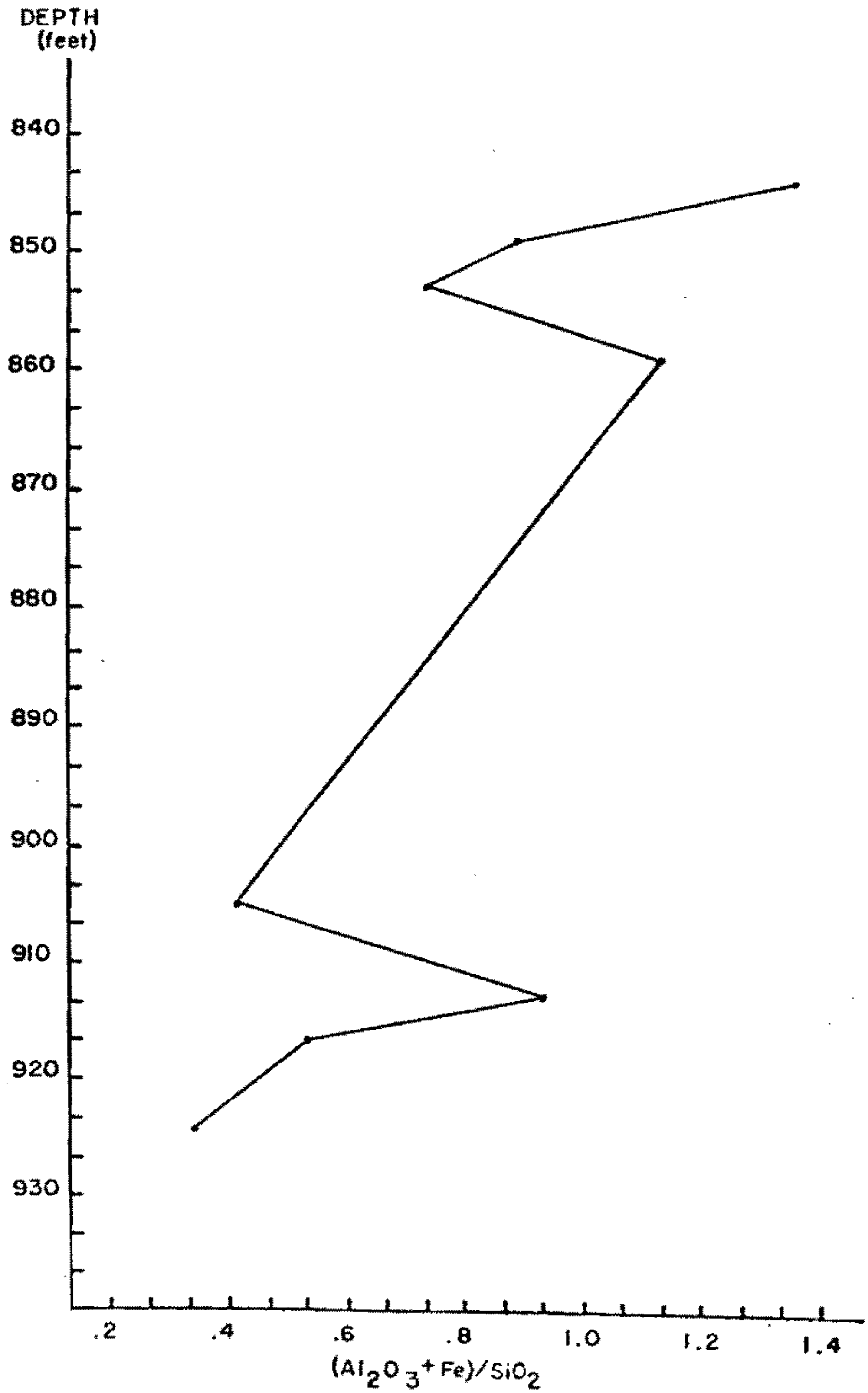
Fig. 16. On-end view of portion of core shown in Figure 15, showing pisolitic kaolinite. 2½ in. (6.35 cm) diameter core.



pisolites are of quartz, or iron-bearing kaolinite, or quartz with rims of iron-rich kaolinite.

Silica concentrations generally decrease, varying as a function of alumina and iron concentrations (Figure 17).

Fig. 17. Plot of [Al_2O_3 + total iron (expressed as Fe_2O_3)]/ SiO_2 versus depth, well 1.


DEPTH
(feet)
840
850
860
870
880
890
900
910
920
930
.2
.4
.6
.8
1.0
1.2
1.4
$(Al_2O_3 + Fe)/SiO_2$

INTERPRETATION AND DISCUSSION

General Trends in Weathering Profile

From the chemical data in Figures 7, 8, 12, 17, and 18 and Table 3, a sequence of relative mobility of cations can be determined. Generally calcium, sodium and magnesium are the most mobile elements, lost in the early stages of weathering. Aluminum is the least mobile element and shows relative increases in concentration through weathering. Potassium and silicon are intermediate in chemical mobility. They decline in concentration only in the latter stages of weathering. This trend is most apparent in the profiles developed on granitic rocks, owing to their relatively homogeneous original composition, but it can also be discerned in the profiles developed on schist. The behavior of iron is difficult to determine, and will be discussed later.

The sequence of relative mobility of cations observed in Red River Valley rocks closely resembles those of Goldich (1938), Brock (1943), Yamasaki et al. (1955), Harriss and Adams (1966), and Wolff (1967). Of these studies, all but Goldich's concern modern weathering profiles.

The sequence of chemical stability is a reflection of the order of mineral stabilities observed in this study. Plagioclase, amphibole, and biotite are the first minerals to break down. Muscovite and alkali feldspar are destroyed in the intermediate stages of alteration. Quartz may be slightly altered in the most extremely weathered material. The order of mineral stability agrees with those observed by the authors cited above.

Evidence for in situ Weathering

As discussed above, chemical and mineralogical trends in the Red River Valley weathering profile are much like those observed by many authors working on exposed, modern weathering profiles developed on crystalline rocks.

Height/width ratios of the 7Å kaolinite peak increase upward in the profiles. The height/width ratio is a measure of size and/or degree of ordering of kaolinite crystals. Relatively broad peaks indicate small and/or disordered kaolinite crystals (Brindley 1961). Decrease in crystal size and degree of ordering with depth is expected in an *in situ* weathering profile (Prichard 1980). The amount of kaolinite decreases with depth in the profile as the amount of feldspar increases, which is also expected in an *in situ* weathering profile (Figure 10).

Further evidence for an *in situ* weathering origin for the kaolinitic zone are traces of metamorphic rock fabric which remain in the weathered material (Figure 5). The most viable explanation for all these conditions is that the weathering is *in situ* and the kaolinite is residual.

Formation of Kaolinitic Zone

Nearly all kaolinite is formed in weathering profiles in leached acidic environments (Dunoyer de Segonzac 1970). Kaolinite forms through the removal of cations (e.g. Ca^{++}, Na^{+}, K^{+}) from other silicate minerals (e.g. feldspars, micas, amphiboles) present in the parent material (Degens 1965). Conditions favorable for leaching include:

1. rainfall in excess of evaporation
2. acidic pH
3. permeability in parent rock

In addition, a warm climate, and a flat land surface further the development of kaolinite in weathering profiles. These conditions imply a tropical to sub-tropical climate with high rainfall and abundant vegetation. McNeil (1964) shows that such environments produce modern kaolinitic or lateritic weathering profiles.

Reactions involved in the transformation of minerals common in crystalline rocks to kaolinite can be summarized as follows:

1) $$\underset{\text{rainwater}}{H_2O} + \underset{\text{from atmosphere}}{CO_2} \rightleftharpoons \underset{\text{carbonic acid}}{H_2CO_3} \rightleftharpoons 2H^+ + CO_3 \quad \text{(a)}$$

2) $$\underset{\text{albite}}{3NaAlSi_3O_8} + \underset{\text{from carbonic acid}}{2H^+} \rightleftharpoons \underset{\text{paragonite}}{NaAl_3Si_3O_{10}(OH)} + 2Na^+ + 6SiO_2 \quad \text{(a)}$$

3) $$\underset{\text{paragonite}}{2NaAl_3Si_3O_{10}(OH)_2} + 2H^+ + 3H_2O \rightleftharpoons \underset{\text{kaolinite}}{3Al_2Si_2O_5(OH)_4} + 2Na^+ \quad \text{(a)}$$

4) $$\underset{\text{alkali feldspar}}{3KAlSi_3O_8} + 2H^+ \rightleftharpoons \underset{\text{sericite or muscovite}}{KAl_3Si_3O_{10}(OH)_2} + 2K^+ + 6SiO_2 \quad \text{(a)}$$

5) $$\underset{\text{sericite or muscovite}}{2KAl_3Si_3O_{10}(OH)_2} + 2H^+ + 3H_2O \rightleftharpoons \underset{\text{kaolinite}}{3Al_2Si_2O_5(OH)_4} + 2K^+ \quad \text{(a)}$$

6) $$\underset{\text{biotite}}{2K(Mg,Fe)_3AlSi_3O_{10}(OH)_2} + 14H^+ + H_2O \rightleftharpoons \underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4} + 2K^+ + 6(Mg,Fe)^{++} + \underset{\text{silicic acid}}{4H_4SiO_4} \quad \text{(b)}$$

(a) from Garrels and Christ (1965)

(b) modified from Garrels and McKenzie (1971)

In all the above reactions, the original minerals are altered by the presence of aqueous acids. The end products are kaolinite, with intermediate products in equations (2) and (4). Alkali ions are released into solution. Equations 2-5 suggest the presence of amorphous silica in the weathering products. This is not observed in the Red River Valley weathering zone, which suggests that silica went into solution and was removed from the system.

Comparison of Weathering Products of Granitic Rocks and Schist

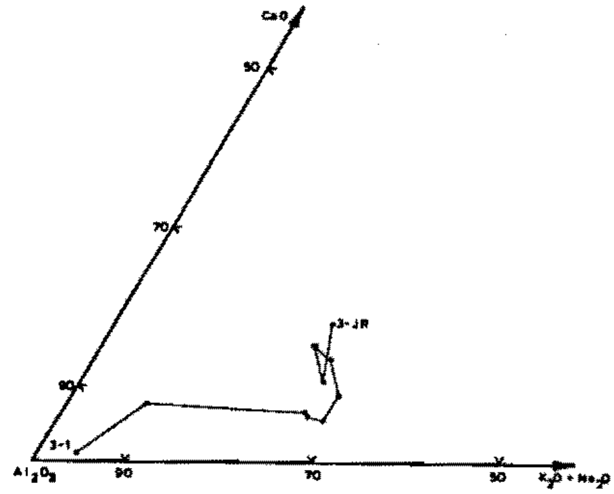
The end products of weathering of granitic rocks and the generally more mafic schists in the Red River Valley are similar in texture, mineralogy, and chemistry. The final product of weathering of either granitic rocks or schist is a massive kaolinite containing suspended angular quartz grains. The residual clay is relatively enriched in Al_2O_3 and depleted in CaO, MgO, Na_2O, K_2O, and SiO_2. Regardless of parent rock, the weathering products approach a clay-rich aluminous end product (Figure 18).

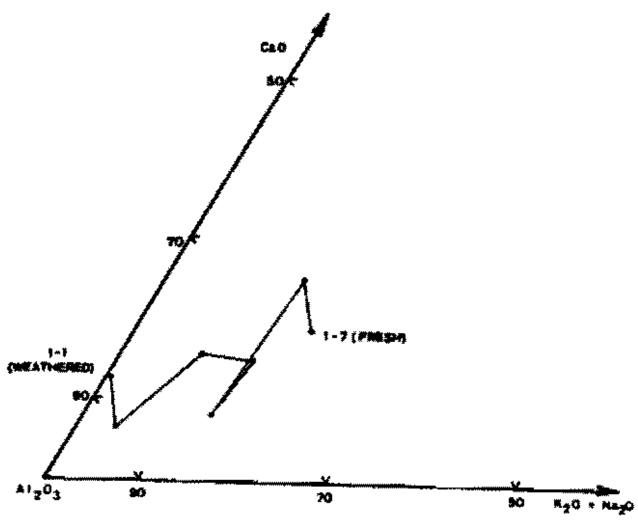
The distribution of iron in the weathering zone is erratic. In profiles developed on granitic rocks, iron concentrations are uniformly low (2-5%) in unweathered material, and increase or decrease very slightly in the weathered zone. Fresh schist typically contains 2-10% iron. Analyses of weathered material show the iron content to increase to 30% or more (well 1) or to decrease with weathering (well 6). In some profiles, iron concentration increases and then decreases in the weathering profile (well 8). The variation in the distribution of iron can be explained in two ways. First, the variations are inherent from the original rock. Second, the variations are a result of localized oxidation-reduction conditions. Iron solubility is redox-dependent,

Fig. 18. Ternary plots of Al_2O_3 versus $K_2O + Na_2O$ versus CaO (Ossan's diagram) for wells 1 and 3.

18a. Ossan's diagram for well 3. Line segments connect analyses from freshest (3-JR) to most weathered (3-1) samples.

18b. Ossan's diagram for well 1. Line segments connect analyses from freshest (1-7) to most weathered (1-1) samples.


CaO
50
70
90
3-1
3-JR
Al2O3
90
70
50
K2O + Na2O


CaO
50
70
90
1-1
(WEATHERED)
1-7 (FRESH)
Al2O3
90
70
50
K2O + Na2O

and iron is nearly insoluble under oxidizing conditions in the form of Fe_2O_3. Localized changes in redox potential could cause concentrations of iron in some parts of the weathering zone and removal in others.

Variability in the composition of the original rocks seems the most likely explanation for the variability in iron concentration because iron concentrations are relatively constant in many of the weathering profiles developed on granitic rocks.

In the fresh rock, iron is in the form of biotite, chlorite and amphibole, with minor amounts of pyrite and magnetite. In the weathering products, siderite is the only iron-bearing mineral present in quantities large enough to be detected as a discrete mineral phase. Iron oxides and hydroxides are not detected as discrete mineral phases, but apparently are present, and give a brown or red color to clay minerals. Carroll (1970b) found iron to be oxidized in the form Fe_2O_3 in the weathering products of a granite, and dispersed to give a brown color to clay minerals.

Regional Controls and Age of the Weathering Surface

Age of the Weathering Surface

As noted previously, the zone of weathering is usually overlain by late Cretaceous rocks. Exceptions are wells 12, 24, 26, and 31A, in which the weathered zone is overlain by Pleistocene glacial, glaciofluvial, or glaciolacustrine sediments, and well 8, where the weathered Precambrian is overlain by Ordovician rocks.

The weathered sections in wells 12 and 24 are overlain by material which is apparently reworked weathered Precambrian rock. Its age of deposition is unknown.

The area around well 31A is structurally high, and forms the divide between Hudson Bay and Gulf of Mexico drainage. If the area was not protected by Cretaceous cover during subsequent glaciation, being structurally high probably prevented it from extensive glacial erosion. As an alternative, a thin Cretaceous cover could have been eroded, exposing the weathered Precambrian to subsequent deposition of glacial sediments.

The weathered zone in well 26 is 78 ft (24 m) thick. It may have been two or three times this thick prior to removal of part of the material by glacial erosion. Again, a thin Cretaceous cover could have been removed by glacial erosion, leaving the weathered Precambrian relatively untouched.

The bulk of the weathered material is clearly pre-Cretaceous, as it is immediately overlain by strata of Cretaceous or younger age. Slightly to moderately altered material very similar to the pre-Cretaceous weathered material is found beneath Ordovician rocks in well 8. This suggests that (a) all of the weathering may have occurred prior to Ordovician sedimentation. Areas which are now covered by Cretaceous strata may have been exposed during the intervening time, or they may have been covered by strata older than Cretaceous, which was removed subsequent to deposition of Cretaceous sediment; (b) there were several weathering events, one pre-Ordovician, and one or more prior to Cretaceous sedimentation; or (c) there was episodic kaolinite formation by chemical weathering, interrupted by marine transgressions and periods of physical weathering from prior to the Ordovician sedimentation until the Cretaceous.

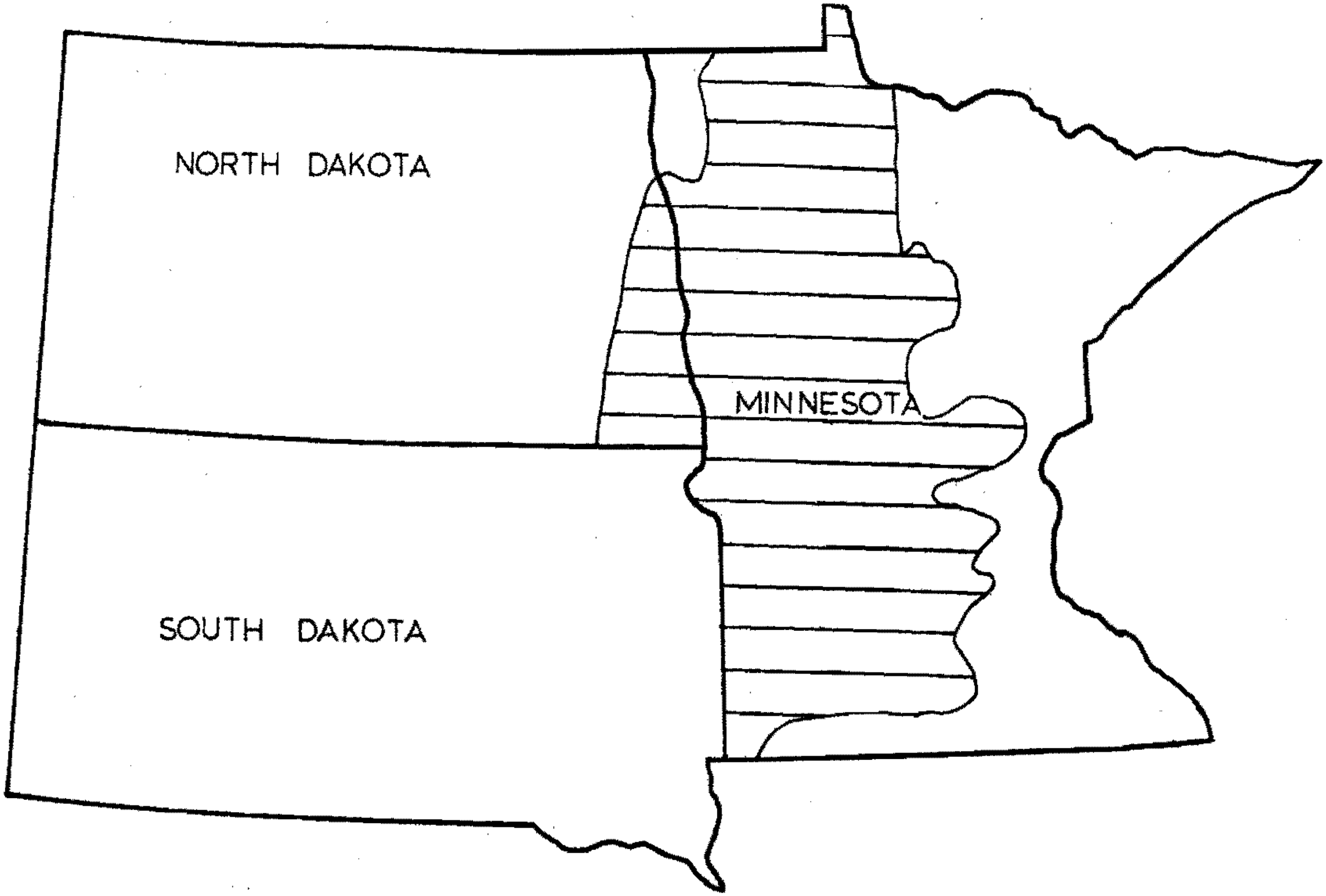
I am unable to determine which of these hypotheses is correct. Several weathering zones are known to be developed on Paleozoic carbonates in the Williston Basin. Carlson and Anderson (1965) state that many of the Paleozoic units of the Williston Basin owe their present eastern limits to erosion. Both of the above lend credence to (c). The pre-Cretaceous weathering zone apparently extends onto the Ordovician carbonates in the northern part of the Red River Valley. A red clay was observed in cuttings from the Ordovician-Cretaceous contact in several wells, which is probably a terra rosa (Moore 1978).

Austin (1970; 1972) hypothesized an abrupt climatic change in the early late Cretaceous (Cenomanian) which halted the kaolinite formation. He states that the weathering probably commenced sometime after middle Devonian, as rocks as young as Devonian are weathered in Minnesota. His ideas regarding the end of the weathering are reasonable, but untestable with present data. The Red River Valley weathering zone presents no evidence regarding the earliest age of weathering. Austin's suggestion for the earliest age of weathering is not conclusive, since there is a pre-late Cambrian weathering regolith developed on Precambrian rocks underlying the Mt. Simon sandstone near his study area (Morey 1972).

Regional Controls in Weathering

The remainder of the discussion will concern the pre-Cretaceous weathered zone developed on Precambrian crystalline rocks. The geographic extent of the pre-Cretaceous weathering zone on Precambrian basement rocks in Minnesota and North Dakota is shown in Figure 19. The eastern margin of the weathering zone roughly corresponds to the

Fig. 19. Extent of pre-Cretaceous weathering zone on Precambrian basement rocks in North Dakota and Minnesota. Modified from Sloan (1964), Parham (1970), with additions from the present study.


NORTH DAKOTA
MINNESOTA
SOUTH DAKOTA

eastern limit of Cretaceous rocks in Minnesota (Sims 1970). The western boundary roughly corresponds to the edge of the area of Precambrian rocks which are directly overlain by Cretaceous rocks (Anderson 1974). The weathering horizon may have developed well beyond its present eastern limit, but was eroded by pre-glacial (Tertiary) erosion or Pleistocene glaciation. The overlying Cretaceous material apparently served as a protective cap during glaciation.

The origin of the weathering zone has been discussed by Goldich (1938), Sloan (1964), Parham (1970; 1972), and Parham and Hogberg (1964). Their ideas can be summarized as follows:

Based on understanding of the general conditions required for the formation of kaolinite, and paleobotanical information from the overlying late Cretaceous sedimentary rocks, these authors postulate that the weathering took place under humid, subtropical conditions in a mixed deciduous-conifer forest. They feel that conditions in the Jurassic were not conducive to kaolinite formation, but as Cretaceous seas encroached on what is now North Dakota and Minnesota, the climate warmed, and rainfall increased. In other words, the rate of Kaolinite formation increased as the Cretaceous shoreline transgressed. The rate of kaolinite formation accelerated as late Cretaceous time approached, so that the bulk of the kaolinite formed in less than five million years in the early late Cretaceous. Parham (1970; 1972) further suggested that the Precambrian surface was a peneplain during the late Cretaceous, inhibiting transport of the weathered kaolinite, leading to a thick buildup of <u>in situ</u> weathered material.

This hypothesis assumes that encroachment of the Cretaceous sea is the sole reason for the warming of the climate of the upper midwest.

Their arguments apparently assume that North Dakota and Minnesota were at the same latitude in the past as now. However, most plate tectonic reconstructions show North America at lower latitudes during the Cretaceous--in fact, during most of the late Paleozoic and Mesozoic, North Dakota and Minnesota would have been in a subtropical zone.

Modern lateritic and kaolinitic weathering profiles are developed mainly in humid subtropical climates, regardless of proximity to oceans (McNeil 1964; Carroll 1970b). With the recent paleogeographic information, it no longer seems necessary to invoke the proximity of Cretaceous seas as the agent for warming the climate.

Recommendations for Future Study

Future studies of the stratigraphy of the Red River Valley may add to existing work by determining more closely the age(s) of weathering.

Canadian shield rocks have been supposed as the source material for Williston Basin clastic rocks (Bjorlie 1979). However, the shales in the Williston Basin are generally not kaolinitic, but illitic. Future studies may determine whether the clastic material was altered by depositional or diagenetic processes, or whether weathering which resulted in non-kaolinitic products occurred.

Large amounts of metal were removed from the Precambrian basement rocks during weathering. If the waters which carried the metals were routed so that these metals could have been concentrated, the possibility exists for discovery of stratiform or stratabound ore deposits in the eastern Williston Basin.

The Vermillion fault and the northeast-trending shear zones may be sites of potential mineralization, and should be investigated further.

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